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*Westoe Coal Preparation Plant in the Durham Division of the National Coal Board*

# *Two Modern Coal Preparation Plants in Durham Division of the National Coal Board*

By A. R. JOHNSON, B.Sc., A.M.I.Mech.E., A.M.I.E.E., A.M.I.Prod.E., Newcastle-upon-Tyne Branch.

COAL AND MORE COAL is an urgent need of the nation. More coal is required for power stations, for gas works and coke ovens, for industry, for domestic use and for export. In an attempt to satisfy this growing demand, extensive mechanisation both underground and on the surface has been carried out at many collieries. While the emphasis is on quantity, the standard of quality must still be maintained. The removal of as much as possible of the associated dirt or incombustible matter from coal as it is mined, together with subsequent grading according to size, benefits the consumer in every industry and thereby increases its marketing value.

The percentage of incombustible or non-bituminous matter such as stone, shale, clays and pyrites found in the coal as mined has considerably increased during recent years for the following reasons:—

1. Most seams of high quality easily worked coal, particularly in districts near the shaft, have been worked out, and seams are now being worked which were previously classified as uneconomical because of the associated dirt. Dirt may occur in bands of varying thickness running through the coal seam or as pockets of incombustible material in the coal itself.
2. Not very long ago, the 'getting' and filling of coal into tubs at the coalface was done by hand, and a certain amount of selection could be maintained. Present-day methods, using electrically driven coal cutters with power loading on to conveyors, or even hand filling on to conveyors, do not lend themselves to the separation of dirt from coal at the coalface.
3. If the material directly above the coal seam is laminated shale, when the coal is removed, inevitably some of the shale will fall and be transported with the coal to the surface.
4. In thin seams, in order to obtain the maximum yield of lump coal, it is often the practice when using coal cutters to undercut into the material directly below the coal seam. This can lead to considerable quantities of dirt being added to the coal.

To deal with the problem the National Coal Board are building Coal Preparation Plants, commonly known as Washeries, the object of which is the removal of dirt or incombustible material as it leaves the pit.

**Wardley and Westoe Collieries**

This article describes the general features of a modern coal preparation plant, and is based on the plants recently erected in No. 1 Area of Durham Division at Wardley Colliery by Messrs. Nortons-Tividale Limited, and at Westoe Colliery by Messrs. Simon Carves Limited. The drives for all equipment in both installations are provided by 'English Electric' motors, and it is the author's intention to illustrate the application of these motors by describing the processes which are involved in a typical coal preparation plant. It is interesting to note that both Nortons-Tividale and Simon Carves are at present erecting further plants in Durham Division, and 'English Electric' motors are again being used.

No attempt is made to detail the mechanical equipment or electrical control circuits, for while the two plants are similar in many respects both have design features which are peculiar to the respective manufacturers. Further, many factors, such as the quantity and quality of coal to be

cleaned, and the quality and size of the final product demanded by marketing considerations, necessitate each installation being designed to meet individual requirements.

**The Principles of Coal Cleaning**

The majority of coal cleaning processes depend for their action upon the difference in the density of coal and its impurities, the lighter coal being recovered whilst the heavier mineral matter is discarded.

Specific gravities of materials occurring in raw coal are as follows:—

| | |
|---|---|
| Bituminous coal .. .. | 1·12 to 1·35 |
| Middlings .. .. .. | 1·45 „ 1·7 |
| Carbonaceous shale .. | 1·7 „ 2·2 |
| Clay .. .. .. .. | 1·8 „ 2·2 |
| Shale .. .. .. | 2·0 „ 2·2 |
| Sandstone .. .. .. | 2·2 „ 2·6 |
| Quartz .. .. .. | 2·5 „ 2·7 |
| Mica .. .. .. .. | 2·7 „ 2·9 |
| Pyrites .. .. .. | 4·8 „ 5·2 |

Middlings, mentioned above, are part coal and part dirt, and these can generally be mechanically separated by crushing. While the specific gravity of middlings will vary according to the proportion of coal and shale, it is seldom profitable to separate middlings having a specific gravity over 1·7.

A number of systems are used for cleaning coal. Some involve the preparation of a dense medium by the addition of barytes, magnetite, or sand to water to increase its specific gravity to a calculated value. Coal will float on the medium while mineral matter sinks to the bottom. Separation of coal from dirt is thereby achieved.

At Westoe and Wardley Coal Preparation Plants however, a different method known as the Baum type jig washer is used. This involves the use of compressed air to effect the necessary pulsation of a bed of raw coal in order to form it into layers according to the specific gravities of the constituent materials.

The Baum washbox is a large fabricated tank, longitudinally divided into an air-chamber and a washing chamber (see Fig. 1). Into the air-chamber is lead the water supply and compressed air which is given a pulsating motion by the operation of rotary or reciprocating air valves. The washing chamber is open to the atmosphere and is provided with a perforated metal plate below water level on which the raw coal forms a bed as it is fed into the washbox. When the air valves are closed, the compressed air at a pressure of about 2-3 lb/sq in depresses the level of the water in the air-chamber and correspondingly raises it in the washing chamber, giving a quick lift to the bed of raw coal.

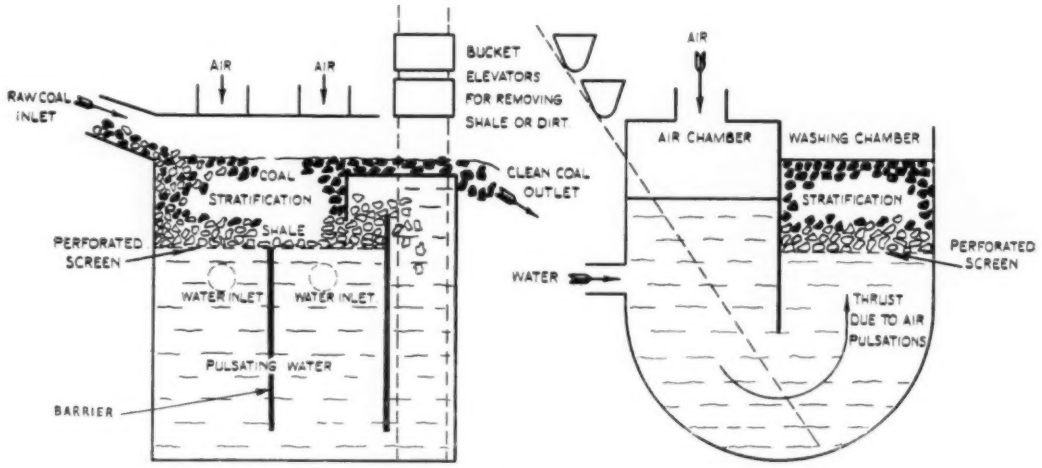


*Fig. 1.—Sections illustrating the principle of the Baum Washbox*

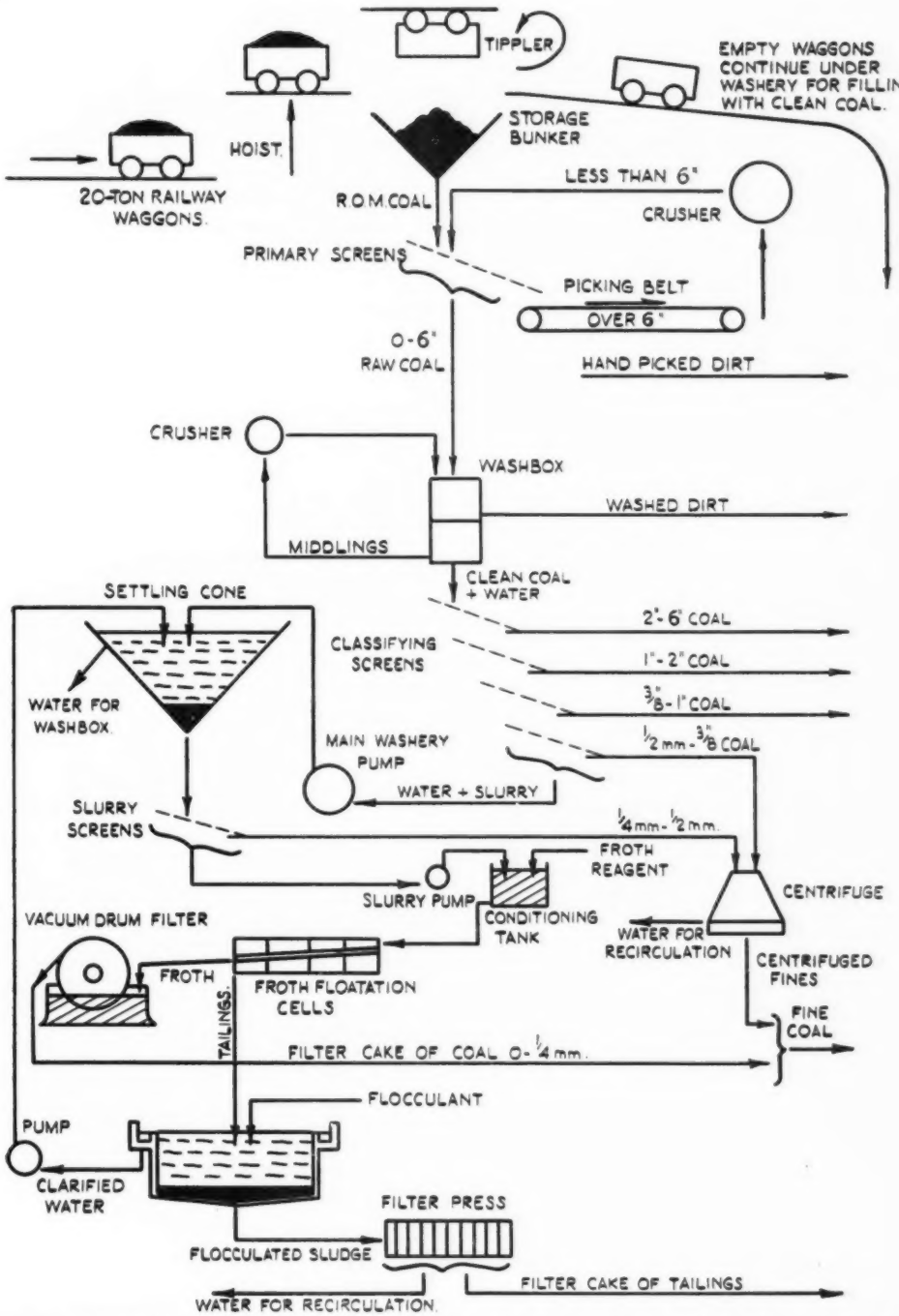


*Fig. 2—Simplified flow diagram to illustrate the principle of operation of a coal preparation plant.*

A period of suspension follows during which the bed becomes stratified, that is, the raw coal grades itself according to the specific gravity of its components. Heavy dirt will quickly settle to the bottom of the bed, the lighter coal at the top, and middlings in between. When the air valves open to atmosphere, the level of the water in the air-chamber returns to that in the washing chamber, and the cycle is complete. The number of cycles per minute is of the order of 40-60.

A determined quantity of water is fed into the side of the air chamber, flowing through the bed of raw coal and over a weir at the end of the washbox. The flow of water removes the top layer of the bed, which is coal, carries it over the weir and on to the jigging classifying screens. The screens remove the water and grade the coal into various sizes. While the coal is being floated over the weir, dirt which is denser than coal settles on the bottom of the bed and is taken through a refuse gate and thence by bucket elevator to a refuse conveyor for disposal. Fine particles of dirt which pass through the perforated screen supporting the bed of raw coal are also removed by the bucket elevator.

In order to effect the separation of coal and middlings the washbox is divided into two sections. In the first the heavy dirt sinks immediately to the bottom of the bed and is removed as refuse. Coal together with middlings passes over the first weir and re-washing takes place in the second compartment. This time the middlings and light shale form the bottom of the bed which is removed through the refuse gate, lifted by bucket elevator to a crusher, and returned to the first compartment for re-washing.

The degree to which coal is cleaned can be regulated by adjusting the water supply, air pressure, and refuse discharge gates.

**The Coal Preparation Plant**

While the functions of a coal preparation plant can be simply stated as the cleaning and grading of coal, the practical application is complicated by the fact that 'run of mine' (R.O.M.) coal varies considerably in both size and quality. Further problems are presented by the necessity of using a closed water circuit, and at the same time preventing an undesirable concentration of solids in suspension.

The coal preparation plants at Wardley and Westoe can conveniently be divided into the following sections:—

1. Raw coal plant.
2. Washery.
3. Slurry treatment plant which involves:—
   (*a*) Froth flotation equipment and rotary vacuum drum filters.
   (*b*) Flocculation plant and refuse filter presses.

To illustrate the process described below a simplified flow diagram is shown in Fig. 2.

RAW COAL PLANT

Before the coal can be fed into the washbox at a constant rate, and of a size which will enable efficient cleaning to take place, waggons must be discharged, large pieces of dirt removed by hand, ferrous metals removed by magnetic drums and large coal crushed.

At Westoe, waggons bringing R.O.M. coal from neighbouring collieries are hoisted 22 feet to the

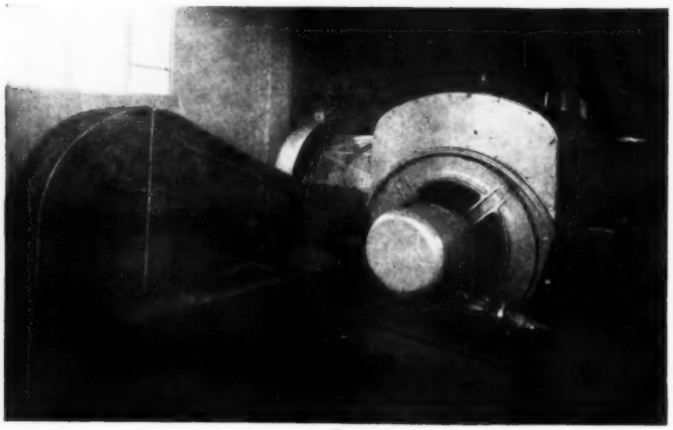

*Fig.* 3.—150 *h.p.* 720 *r.p.m. closed-air-circuit slipring motor driving raw coal plant waggon hoist at Westoe*

tippler level by pushbutton-operated automatic hoists each driven by a 150 h.p. slipring motor (Fig. 3). The 55 h.p. tipplers lift and invert each full waggon so that its contents are emptied into large concrete storage bunkers. From the bottom of the bunkers vibro-feeders provide a steady discharge on to primary screens which grade the R.O.M. coal into sizes of 1 to 0 inch, 6 to 1 inch, and above 6 inches. The 1 to 0 in and 6 to 1 in raw coal is taken by conveyor to further storage bunkers above each washbox in the washery building. The gantry for these conveyors can be seen in the frontispiece. R.O.M. coal above 6 inches is fed on to a picking belt where large pieces of obvious shale are removed by hand. The coal passes through crushers and then back to the primary screens for regrading. Crushing not only prevents jamming of the washbox by oversize material but also helps to separate any shale which may be contained in the coal.

At Wardley the arrangements are similar but not so elaborate, as the capacity of the plant is 200 tons per hour compared with 500 tons per hour at Westoe. In this case waggons are discharged by hand into a track hopper and then taken by conveyor to the raw coal plant storage bunkers. The maximum size is again limited to 6 inches, but further grading on primary screens is not carried out, as the plant is designed for one washbox only. At Westoe however, to achieve the greater throughput, two washboxes deal with 6 to 1 in raw coal and two washboxes with 1 to 0 in raw coal.

R.O.M. coal is not only delivered by railway waggons to Westoe Coal Preparation Plant but is also fed to the Raw Coal Section by a conveyor direct from Westoe Colliery. In fact, when Westoe Colliery is completely reconstructed, the bulk of the coal to be cleaned will be transported by direct pit-to-washery conveyor. This arrangement also applies to Wardley.

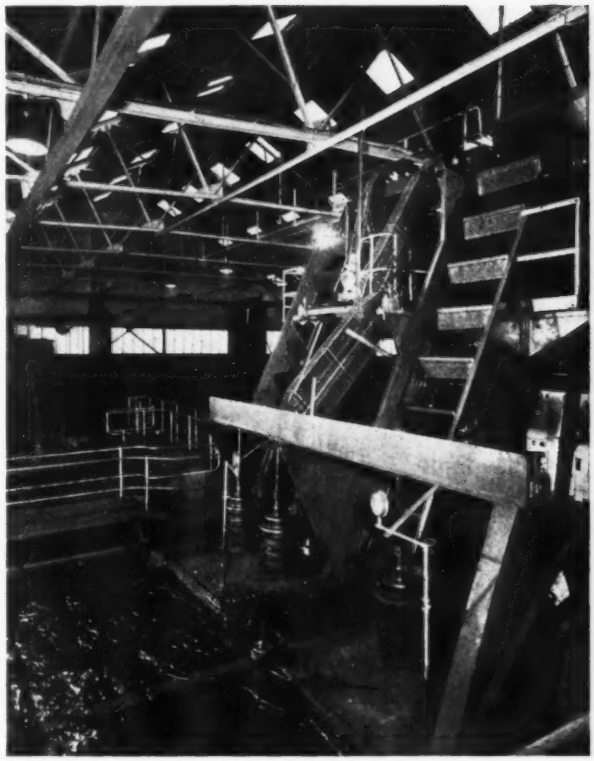

*Fig. 4.—The washbox at Wardley Coal Preparation Plant, from coal input end*

## WASHERY

As already mentioned, at both Wardley and Westoe the Baum method of separation is used, the principle of which has been described. Fig. 4 shows the washbox at Wardley Colliery viewed from the incoming raw coal end. The two weirs with the classifying screens beyond are shown and also the reciprocating air valves and bucket elevators.

The reciprocating air valves give pulsations which lift the bed of raw coal and allow stratification to take place. The first bucket elevator removes heavy dirt discharged through the first shale discharge gate, while the second elevator removes middlings which are then crushed and re-washed. A continuous stream of water carries the clean coal over the second weir and on to the classifying screens. These are perforated plates jigged to and fro by eccentrics, shown in Fig. 5, to

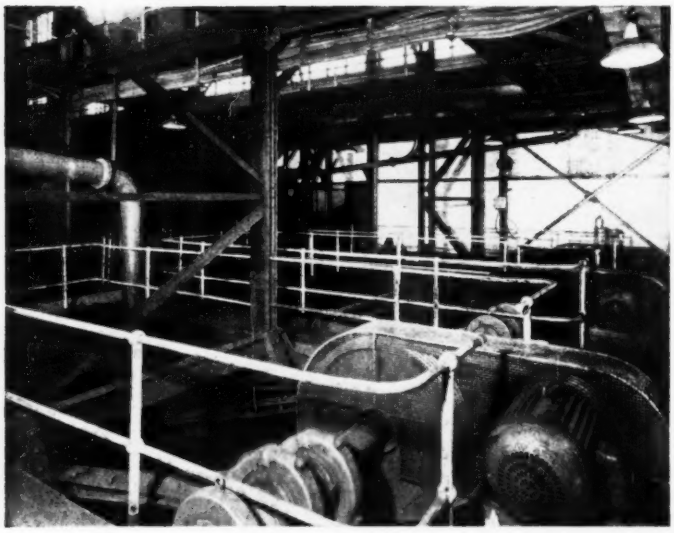

*Fig. 5.—Classifying screens at Westoe, driven by 10 h.p. 730 r.p.m. T.E.F.C. squirrel cage motors*

give a forward motion to the coal. Coal passing through holes in the plates drops on to other screens with smaller holes, and so on, until all the coal has been sized. Conveyors take the graded coal to waiting railway waggons.

The final screens are actually fine wire meshes and remove all remaining solids above $\frac{1}{2}$ mm. These small coals (say $\frac{3}{8}$ in - $\frac{1}{2}$ mm) contain a large percentage of moisture and are therefore centrifuged. Water together with solids less than $\frac{1}{2}$ mm is pumped by 125 h.p. centrifugal pumps (Fig .6) to the top of large concrete settling cones, shown in the frontispiece. A quantity of fine particles in the water settles to the bottom of the cone to form a sludge, which is piped to the slurry screens where solids are removed down to about $\frac{1}{4}$ mm. These fine particles are added to the $\frac{3}{8}$ in - $\frac{1}{2}$ mm small coal before centrifuging.

Fig. 7 shows an inside view of Wardley Washery. Raw coal enters the washbox on the extreme right-hand side and passes on to classifying screens, and sized products leave by conveyors shown in the centre. The fine coal screens are directly below the slurry screens in front of the bucket elevators. On the left-hand side are the froth flotation equipment and rotary vacuum drum filters which are described later.

### Slurry Treatment Plant

As some 2000-4000 gallons of water per minute are required for each washbox it is essential for the water to be re-circulated. The water passing through the slurry screens, however, contains fine particles of coal and dirt in suspension which will eventually produce a high concentration of solids and slimes in the circulating water. Such pollution causes inefficient operation of the washbox due to the varying specific gravity of the circulating ' water '. These fine solids are very abrasive when

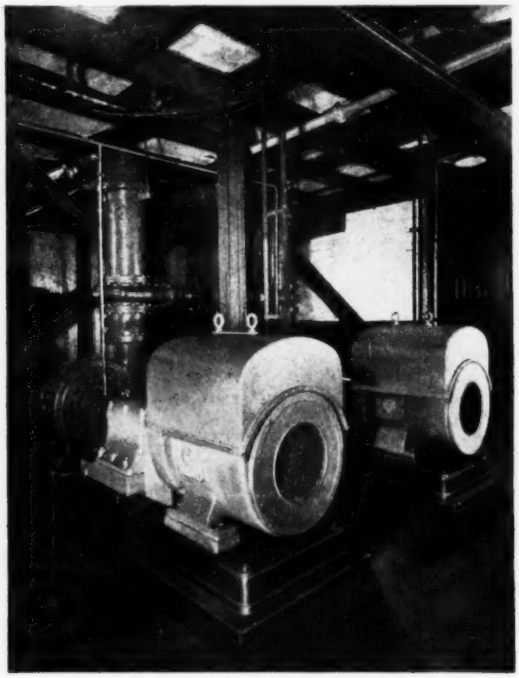

*Fig. 6.—Main washery pumps at Wardley, driven by 125 h.p. 720 r.p.m. closed-air-circuit squirrel cage motors*

in high concentrations, causing considerable wear on pumps, valves, pipelines and screens. They also impose a heavier load on the main pumps, and the outgoing graded coal loses much of its attractiveness by being coated with a layer of fine damp dust.

A method frequently used in the past to keep the solids concentration to a reasonable level when operating a closed circuit system, was to bleed off a quantity of the polluted water and add the same quantity of make-up water. This raised many problems regarding the disposal of polluted water. Rivers and streams were often fouled and, when settling ponds were used, large tracts of valuable ground were lost to the colliery. Coupled with this was the expense of excessive make-up water, and the fact that a vast quantity of good quality coal was wasted.

The modern approach is to treat continually a proportion of the water by froth flotation to remove the fine coal, and flocculate the remaining dirt or tailings to obtain relatively pure water for recirculation. Sludge formed by the flocculation process can easily be caked by filter presses for disposal.

*Froth Flotation*

The effluent passing through the fine slurry screens contains particles of pure coal and dirt. To separate these, use is made of the physical properties associated with the surfaces of the materials, one property which is very familiar

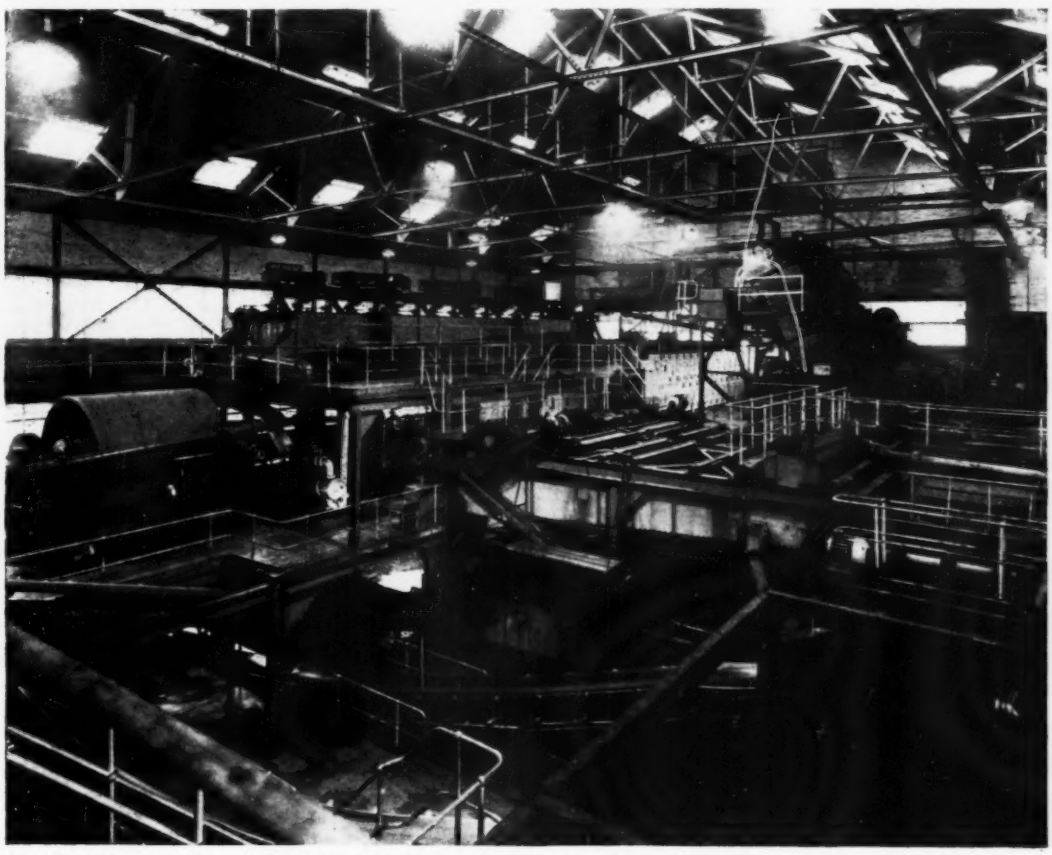

*Fig. 7.—The interior of Wardley Washery, showing classifying screens, slurry screens, froth flotation cells and rotary vacuum drum filter*

being surface tension. The strengths of these properties vary according to the chemical nature of the material and also to a great extent on the degree to which the surfaces of the particles are wetted. Particles of low 'wettability' have a strong molecular attraction and will readily combine with an air bubble and consequently be raised to the surface. Wetting, on the other hand, considerably reduces the strength of molecular attraction so that the particle has little tendency to join an air bubble.

Dirt usually associated with coal is of high wettability, while coal is of low wettability and this can be further reduced by the addition of a suitable oil. Although the oil clings to the coal particles it does not affect the dirt, and the coal thus presents a water repellent or non-wettable surface to the water. By adding a suitable frothing agent and supplying mechanical agitation, masses of small air bubbles will rise to the surface lifting with them the particles of coal to form a fairly stable froth. On the other hand dirt particles, wetted by water, are not affected by the air bubbles and remain in the effluent.

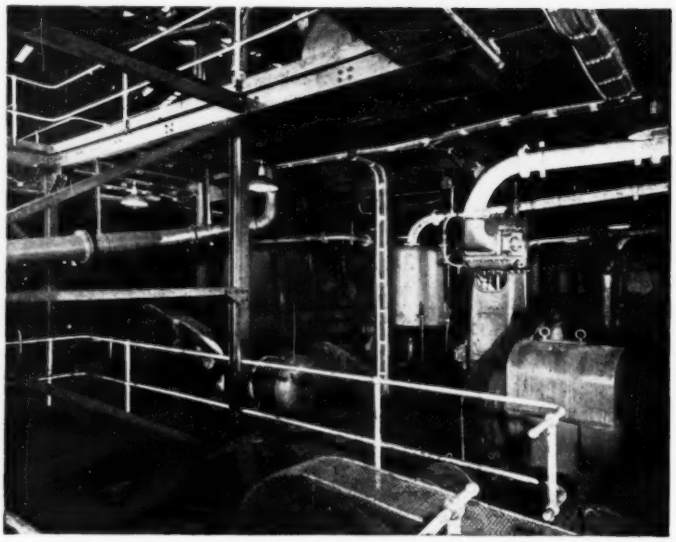

*Fig. 9.—Rotary vacuum drum filter auxiliaries at Westoe, with vacuum pump driven by a 60 h.p. 730 r.p.m. and the screw conveyor by a 20 h.p. 730 r.p.m. squirrel cage motor*

*Fig. 8.—Froth flotation cells at Wardley, each pair of cells having a 20 h.p. 1440 r.p.m. T.E.F.C. squirrel cage motor mounted vertically*

In practice a suitable re-agent is added to a percentage of the effluent from the slurry screens and mixed in a conditioning tank. The conditioned effluent is fed into the first of a bank of froth flotation cells, each of which has an impeller. Vast quantities of small air bubbles float to the surface producing a froth. By using the right type of re-agent it can be arranged for clean coal particles to be carried to the surface securely adhering to air bubbles. A froth of clean coal is then removed from the top of the cells by means of froth paddles (see Fig. 8) and taken to the trough of the rotary vacuum drum filter for de-watering. From the first cell the remaining effluent is passed to the second cell for further frothing, and so on until it has reached the last cell in the unit whence it emerges as an effluent containing the bulk of the dirt or high ash

content particles, with only a very small proportion of coal in suspension. The effluent is passed to the flocculation plant.

*Rotary Vacuum Drum Filter*

A slowly revolving vacuum filter picks up a blanket of the coal-bearing froth and removes most of the moisture present before discharging a relatively dry filter cake on to a conveyor. The conveyor takes the filter cake to a paddle mixer where it is mixed with centrifuged small coal and 'fines' from the slurry screens. The equipment required for the drum filter includes a vacuum pump, vacuum tank, and de-watering pump, as shown in Fig. 9.

While the main object in conditioning the water is to allow a closed water circuit to operate, it has been found that the quantity of coal recovered by froth flotation makes the system economically attractive.

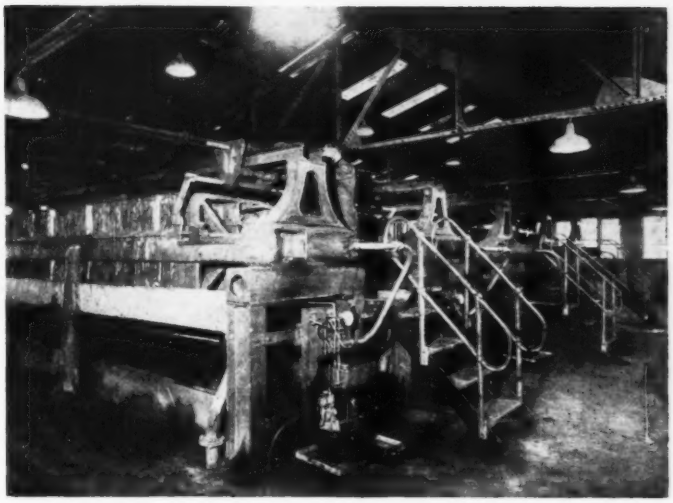

*Fig.* 10.—*Tailings filter presses at Westoe. The hydraulic pump is driven by a* 1 *h.p.* 1450 *r.p.m. T.E.F.C. motor*

*Flocculation*

The effluent, or tailings as it is known, from the froth flotation cells carries only material of high ash content, the pure coal having been removed in the frothing process. Tailings are delivered into a large concrete thickening tank for flocculation and clarification. This tank can be seen on the extreme left-hand side of the frontispiece. A suitable re-agent or flocculant is added which in effect rapidly collects or coagulates the suspended solids in the effluent. The flocculated solids settle at the bottom of the thickening tank whence they are removed as a sludge by a diaphragm pump to the filter presses for de-watering.

The thickening tank is constructed with a launder around the periphery to take off the now clarified water. A raking mechanism slowly revolves, raking the settled sludge into a discharge cone in the centre of the tank.

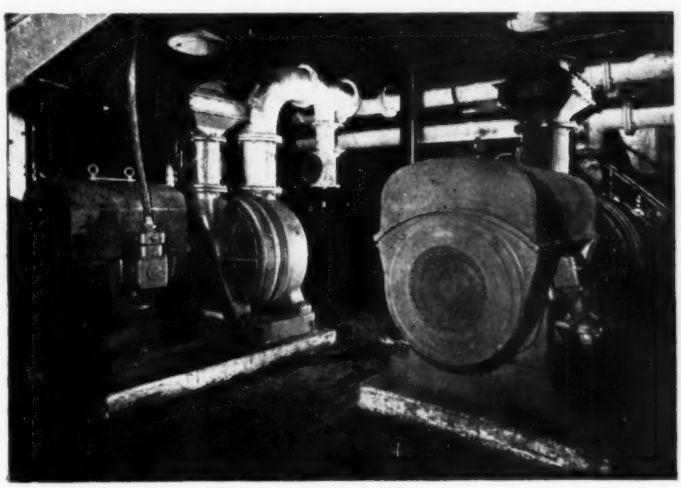

*Fig.* 11.—*Two turbo-blowers at Westoe, one driven by a* 100 *h.p. and the other by a* 160 *h.p.* 2950 *r.p.m. closed-air-circuit squirrel cage motor*

*Tailings Filter Presses*

Flocculated sludge is pumped to filter presses where almost all the water is removed, leaving only a heavy mass of de-watered tailings which are conveyed to a refuse hopper for disposal.

The filter presses consist of a number of iron frames having nylon filter cloths which de-water the tailings supplied under pressure from dead weight pumps. The build-up of de-watered tailings lining each nylon cloth forms a further filter, allowing only clean water to pass through. A bank of such presses is shown in Fig. 10.

**Electrical Equipment**

It will be realised from the foregoing description that the duties of the motors involved in a coal preparation plant cover many types of drive. These include waggon hoists, pumps, large turbo-blowers (Fig. 11), screening plant, crushers and conveyors of many sizes. The two-hundred and thirty 'English Electric' motors installed in the two plants are all totally enclosed, either fan cooled or closed air circuit, and with few exceptions are connected for direct-on-line starting. The only slipring machines are on the hoists and waggon tipplers at Westoe, where the rotor resistances are varied to give speed control. Wherever possible T.E.F.C. motors with standard dimensions to B.S. 2083 : 1954 are employed.

Motors are controlled from cubicle-type contactor boards (not 'English Electric'), automatic sequence of operation or sequence interlocking, according to the scheme employed, being provided for sections of the plant where a correct order of starting is essential. For example, the classifying screens, main pump, elevators, turbo-blower and all associated conveyors must be working before the raw coal is admitted to the washbox.

A large number of emergency stop buttons are conveniently situated throughout the Washery and Raw Coal buildings to enable operators to shut-down sections of the plant immediately.

In addition to the motors, The English Electric Company supplied and installed through its sub-contractors, Messrs. A. Anderson & Son (Electrical Engineers) Ltd., of Middlesbrough, all the cabling at both coal preparation plants.

**Acknowledgments**

Grateful acknowledgment is made to Mr. J. E. Ridley, Chief Engineer of No. 1 Area, Durham Division, National Coal Board, for permission to publish this article. Also to Mr. B. A. Norton, Chief Engineer of Messrs. Nortons-Tividale Ltd ; to Mr. J. E. Chick, Chief Engineer, and Mr. F. Egerton, Chief Electrical Engineer, of Messrs. Simon Carves (Washery Department); and to Mr. E. Dinsdale, Electrical Engineer of No. 1 Area, Durham Division, National Coal Board.

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# *The Napier 'Oryx' Turbo-Gas-Generator Aero Engine*

THE NAPIER 'ORYX' turbo-gas-generator engine is a single-shaft gas turbine designed primarily for operation in helicopters where the rotor is propelled by jet reaction at the rotor blade tips. In this method of propulsion the absence of a reduction gear, driving shaft and geared rotor head effects a considerable saving in installed weight, improves the mechanical reliability and reduces maintenance costs.

The engine performance and handling characteristics benefit from the typical Napier compressor characteristics in which the optimum efficiencies are obtained well removed from surge. This feature permits the operating line to be set at an ample margin from surge, thus permitting good handling qualities without loss of efficiency in normal operation.

Full advantage has been taken of the compressor

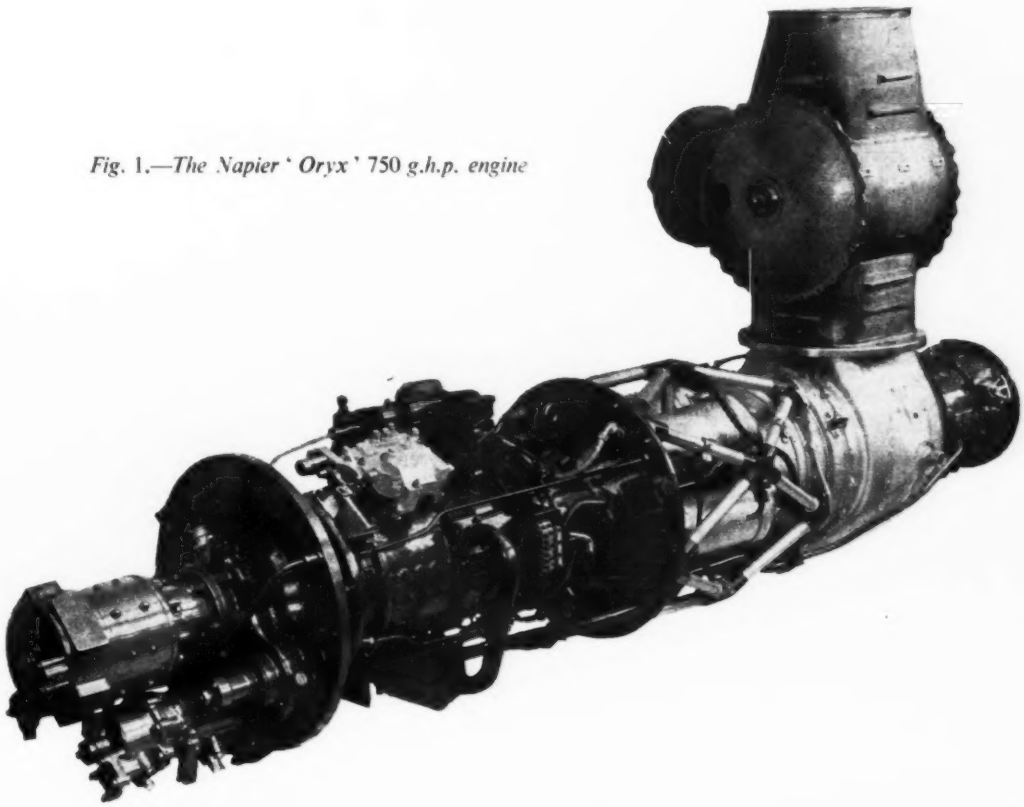


*Fig. 1.—The Napier 'Oryx' 750 g.h.p. engine*

characteristics in the design of the controls, and the engine has a rapid surge-free acceleration. The control system also embodies devices giving instantaneous protection in emergencies in single or multi-engine applications.

The engine has achieved its design performance and completed 2,165 hours of test-bed running. It will shortly be installed in the Hunting-Percival P.74 helicopter, and has also been scheduled as the power unit for the Percival P.105 helicopter. By the end of 1955 a type test to the standard rating of 750 g.h.p. will be attempted and preliminary development at 825 g.h.p. started. It is anticipated that the engine will be developed to 900 g.h.p. by the end of 1956.

The Oryx engine (Figs. 1, 2 and 3) comprises a twelve-stage axial flow main compressor, five combustion chambers, a two-stage reaction turbine and a four-stage axial flow auxiliary compressor. The air from the auxiliary compressor enters a volute in the collector, into which the turbine also exhausts, through a separate volute (Fig. 4). The air and gas are delivered from a flange on the collector to a two-position non-throttling valve which diverts the mixture either to the free exhaust or to the rotor head as required. Control of the engine is effected through an interconnected fuel metering unit operated by a single lever, automatic compensation being provided for changes in ambient pressure and temperature conditions.

**Leading Particulars**

*General*

| | |
|---|---|
| Maximum speed .. .. | 21,900 r.p.m. |
| Direction of rotation (viewed from rear of turbo-compressor unit) .. .. .. .. | Left hand |

*Overall Dimensions*

| | |
|---|---|
| Maximum diameter (excluding collector) .. .. .. | 19¼ in |
| Overall length, excluding accessories .. .. .. .. | 83½ in approx. |

*Weight*

| | |
|---|---|
| Net dry weight (engine terminated at gas collector delivery flange—to E.D.M. No. 25) .. | 495 lb+2½% |
| Non-throttling valve and expansion joint .. .. .. | 60½ lb |

*Gas Mass Flow*

| | |
|---|---|
| Gas mass flow under take-off conditions .. .. .. | 14·4 lb/sec |

*Fuel*

| | |
|---|---|
| Aviation turbine fuel .. .. | D.E.R.D. 2482 |
| Wide cut gasoline .. .. | D.E.R.D. 2486 |

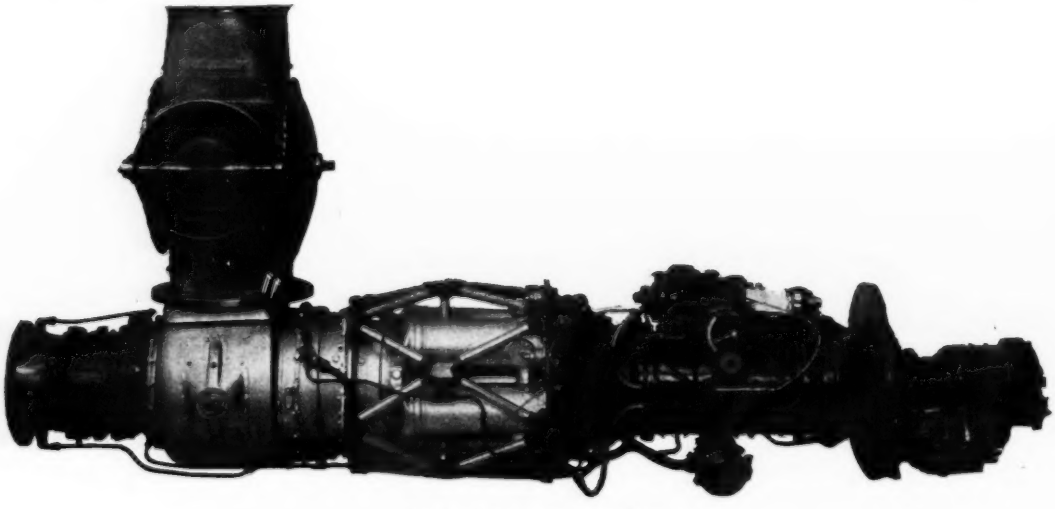


*Fig. 2.—Side view of engine*

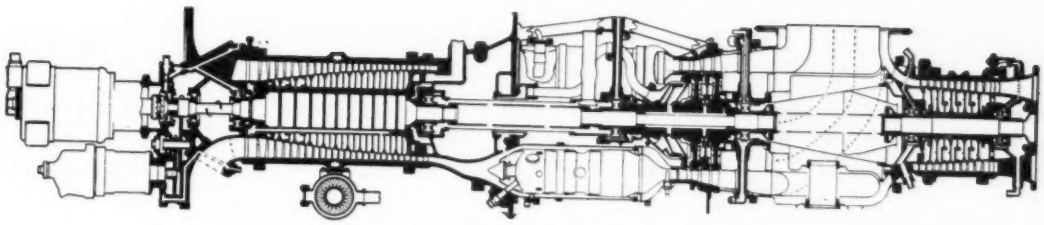


*Fig. 3.—Longitudinal section through engine*

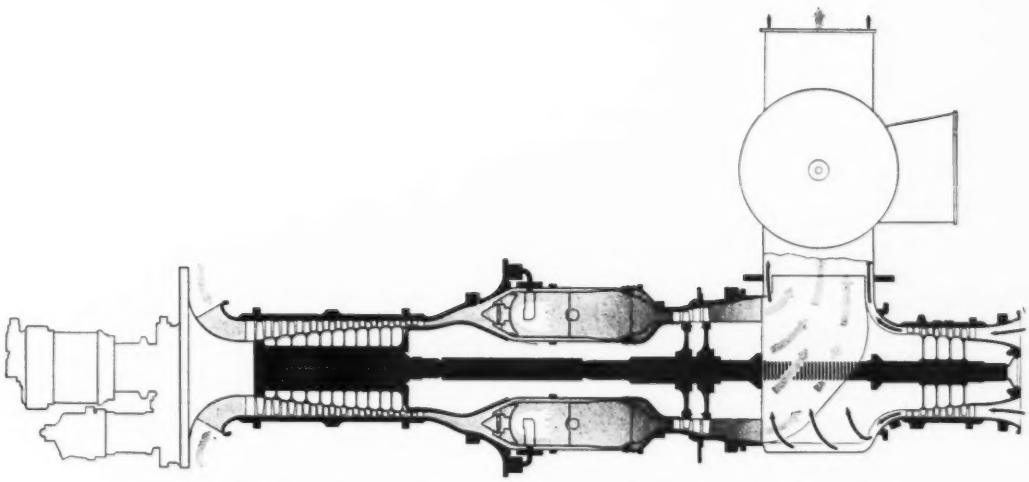


*Fig. 4.—Gas flow diagram (two-way valve rotated 90° from normal position)*

*Lubricating Oil*

Synthetic .. .. .. .. D.E.R.D. 2487

**Performance**

All performance figures are quoted for the standard (I.C.A.N.) atmosphere. The engine has been designed to suit a plenum chamber installation for each compressor. Side intakes have been assumed to be fitted to the plenum chambers and therefore the performance is quoted for static conditions only.

The output expressed in terms of gas horse-power is based on the isentropic temperature drop for the total head to static expansion ratio available at the jet pipe nozzle after the non-throttling valve, and is equivalent to the shaft power that would be developed if the gases were used to drive a turbine having 100% efficiency. The performance quoted is for the engine only and not for the engine-rotor combination in helicopter application.

| Altitude feet | Engine r.p.m. | Gas Mass Flow lb/sec | Expansion Ratio | Gas Temp. °K | Gas h.p. | Spec. Fuel Cons. lb/g.h.p.-hr |
|---|---|---|---|---|---|---|
| *Maximum Power* | | | | | | |
| S.L. | 21,900 | 14·40 | 1·600 | 678 | 750 | ·680 |
| 6,000 | 21,900 | 12·10 | 1·642 | 668 | 645 | ·657 |
| *Maximum Continuous* | | | | | | |
| S.L. | 21,000 | 13·75 | 1·515 | 650 | 610 | ·735 |
| 6,000 | 21,000 | 11·55 | 1·557 | 637 | 530 | ·703 |

Oil consumption, at maximum continuous r.p.m., 1 pint/hr.

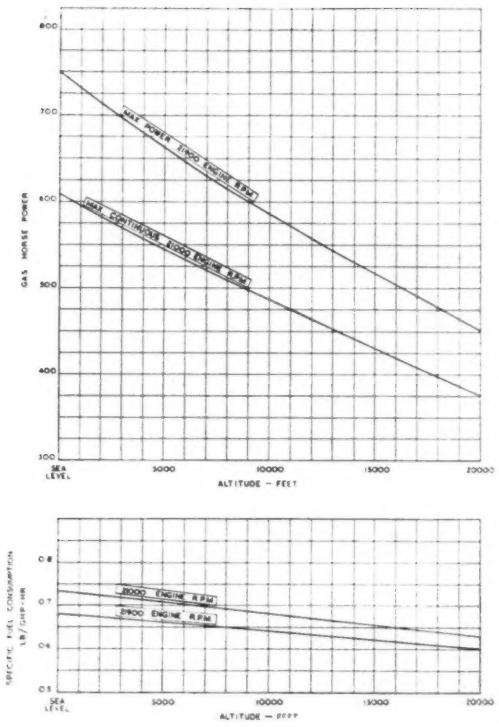



*Fig. 5.—Altitude performance—output and consumption*

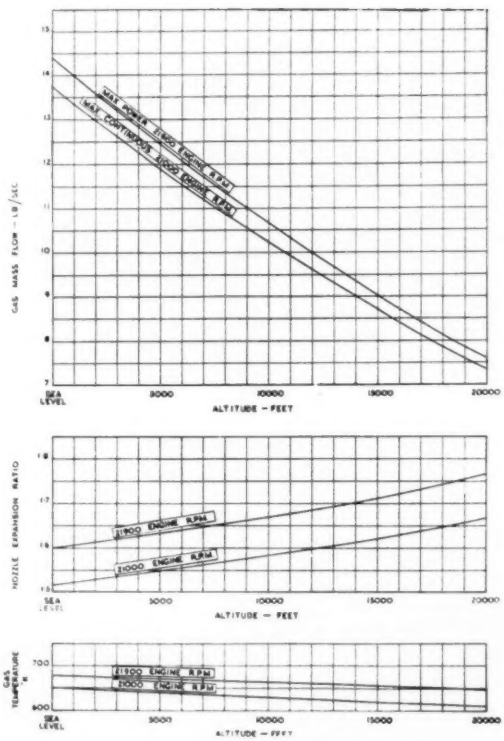



*Fig. 6.—Altitude performance—gas conditions*

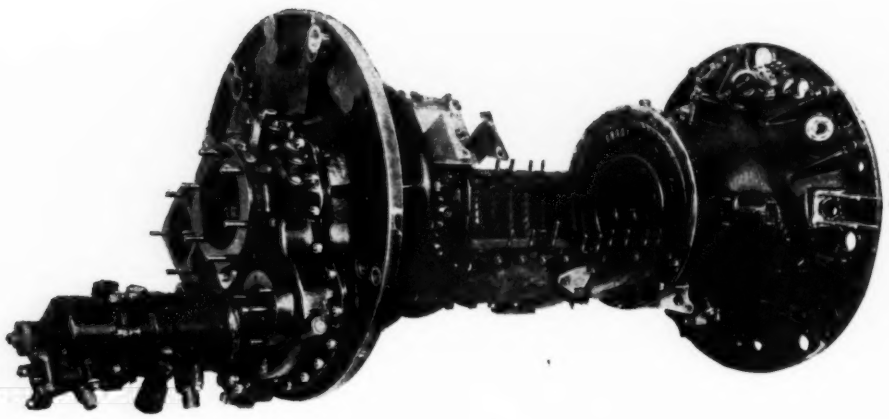


*Fig. 7. Main compressor intake, compressor half-casing and support plate*

Further details of the engine performance are shown by the curves in Figs. 5 and 6.

**Air Intake**

Air is delivered to the main compressor through a radial intake which is cast in RZ5 magnesium zirconium light alloy (Fig. 7). The intake has been designed to suit a plenum chamber installation and, due to this, no provision has been made for protection of the intake against icing or debris. In common with all other gas passages, the intake was flow tested and developed for maximum efficiency and uniform distribution at compressor intake, before incorporation in the final design.

Mounted on the front of the main compressor intake are the engine accessories comprising the fuel pump, oil pressure and scavenge pumps, tacho-generator and the electric starter.

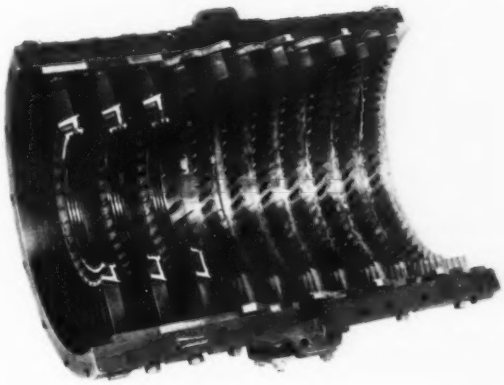


*Fig. 9.—Main compressor half-casing and stators*

*Fig. 8.—Main compressor rotor*

**Main Compressor**

The twelve-stage main compressor of the axial flow type has been designed for a mass flow of 9·9 lb/sec and a pressure ratio of 6·0/1 at 21,900 r.p.m. The rotor is of through-bolted disc construction (Fig. 8) by which means an 'effective' large diameter shaft is obtained although no actual main shaft exists.

Aluminium-bronze blades of Hidurax 1/12A (D.T.D.197/A) are used throughout, and all the rotor blades are secured by fir tree roots to the compressor discs which are of S.62 steel for stages 1 to 11 and S.82 steel for stage 12. The stators, which are of shrouded construction for the first three stages and cantilever for the remainder, are contained in the two halves of the RZ5 magnesium zirconium light alloy compressor casing (Fig. 9).

The complete rotor assembly is supported by a roller bearing at the inlet, and the outlet bearing is a ball bearing housed in the main support plate. A

*Fig. 10.—Rear view of support plate*

muff coupling shaft connects the main compressor shaft to the turbine shaft. The rear compressor bearing and the front turbine bearing compartments are connected by a single drainage sump ; this ensures that the muff coupling shaft serrations are well lubricated by oil mist.

The compressor characteristics obtained give optimum efficiencies on the engine operating line which is well removed from surge. The margin from surge is further increased at low engine speeds by the use of variable inlet guide vanes controlled by a speed-sensing servo unit.

**Support Plate**

The main compressor support plate, a casting in D.T.D.708 light alloy, is situated at the rear of the compressor (Fig. 10). It includes the diffuser, between the compressor and combustion chambers, and an internally cast annulus into which air is bled from the diffuser for turbine cooling purposes.

Provision is made for mounting the engine from four pads, two on the main support plate and two on the collector casing.

**Combustion Chambers**

The combustion system, designed in conjunction with Messrs. Joseph Lucas Ltd., comprises five tubular-type chambers (Figs. 11 and 12) fitted with upstream injection burners. Each burner may be removed separately for inspection without dismantling any other engine part.

Outer casings are fabricated in S.84 material, and the flame tubes in D.T.D.703. The Royal Aircraft Establishment's system of high-energy spark ignition is provided for starting, the equipment being manufactured by The British Thomson-Houston Company or Rotax Ltd. Ignition plugs are provided in two of the combustion chambers from which the flame is propagated to the remainder by interconnectors. The use of upstream injection type burners not only reduces the overall length of the system but gives good combustion at very high air/fuel ratios. Spherical joints are included in the outer casing to allow for slight mis-alignment on assembly.

The engine operates satisfactorily on either kerosine or wide-cut type fuels.

**Turbine**

A two-stage reaction type turbine with an expansion ratio of 3·14/1 has been designed for the Oryx engine. It operates against a high back-pressure as the exhaust gas mixes with the delivery air from the auxiliary compressor ; the leaving velocity and swirl are such that the diffusion required before the volute in the collector is small.

*Fig. 11.—Combustion chamber and burner*

The turbine comprises two separate bladed rotor discs mounted on a shaft and carried in a fabricated casing which contains the two nozzle assemblies. The rotor discs (Fig. 13), of Napier specification DNS 116 steel, are mounted over flank fitting splines on the turbine shaft which is supported at the front by a roller bearing and at the rear by a ball bearing. Drive is imparted to the main and auxiliary compressors by a serrated coupling shaft and a gear-type coupling shaft respectively.

The rotor blades, which are of Nimonic 90 in stage 1 and Nimonic 80A in stage 2, are attached to the discs by fir tree roots. The blades

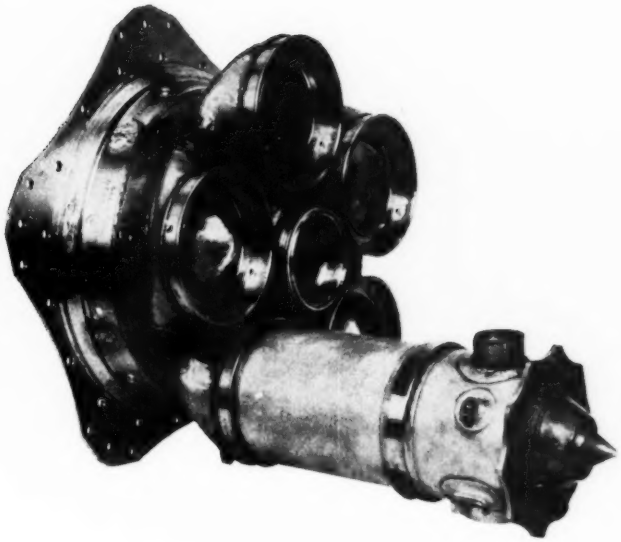


*Fig. 12.—Combustion chamber and turbine inlet casing*

are so fitted in the discs that a limited amount of tip rock is obtained, allowing for the differential expansion of the blades and discs. This relieves the root stresses and ensures a large measure of vibration damping.

Stage 1 nozzle blades are secured by inner and outer rings (Fig. 14) which are fixed to the casing in such a way as to leave them free to expand radially. Stage 2 nozzle blades have inner and outer platforms and are bolted to the external casing. Both stages of nozzle blades are cast in X40 material. The inter-stage seal plate, carrying a seal at the inner diameter and cooling scrolls on each face, is mounted from the nozzle ring by swinging links attached to several of the blade roots (Fig. 15). This arrangement allows for differential expansion and ensures concentricity of the seal under operating conditions.

**Auxiliary Compressor**

The four-stage axial flow auxiliary compressor (Fig. 16) is mounted at the rear of the engine on a common shaft, the direction of air flow being reversed relative to that through the turbo-compressor unit. It is of the conventional shaft and disc type, designed for a pressure ratio of 1·80/1 and an air mass flow of 5·1 lb/sec at maximum r.p.m.

The whole rotor assembly, including the balance piston and seals, is mounted on a splined shaft and is clamped together by means of ring nuts. The shaft is carried in two bearings, a ball bearing at the inlet and a roller bearing at the outlet end. The turbine outlet bearing and the auxiliary compressor outlet bearing have common chambers to ensure oil mist lubrication of the gears on the coupling shaft.

All the blading is of aluminium-bronze, Hidurax 1/12A (D.T.D.197/A), and the rotor blades are fixed to the aluminium discs by fir tree roots. Each of the four stator stages are shrouded and are bolted in the two halves of the RZ5 light alloy casing.

*Fig. 13.—Turbine rotor*

*Fig.* 14.—*Turbine inlet casing and stage* 1 *nozzles*

The inlet guide vanes can be adjusted and set for matching purposes but are not variable while the engine is running. The guide vanes are mounted in the annular intake which is an RZ5 light alloy casting.

**Collector and Valve**

The collector (Fig. 17) is situated between the turbine outlet flange and the auxiliary compressor delivery. It has a single outlet, square in section, through which the turbine exhaust gas and auxiliary compressor delivery air pass, unmixed, to the two-way non-throttling valve. The collector is fabricated in D.T.D.703 steel sheet and contains two separate volutes, one for the gas and one for the air, which turn the flows normal to their original directions. The internal baffling is so arranged that the compressor air surrounds the exhaust gases and thereby keeps the outer casing cool. The outer layer of relatively cool air persists through the non-throttling valve, and the resultant lower casing temperatures ensure satisfactory operation of the valve and reduce the metal temperature of the duct to the rotor head.

The valve (Fig. 18), also of D.T.D.703, is a two-position non-throttling valve, its purpose being to direct the gases during the starting cycle to a nozzle which exhausts to atmosphere, and to divert the gases from the starting nozzle to the rotor head when normal engine operating speeds have been reached. Starting is also facilitated by a butterfly valve in the starting nozzle which has the effect of providing a variable area nozzle. The non-throttling valve is operated by an oil servo unit.

A piston-ring seal-type expansion joint is situated between the collector delivery flange and the two-way valve since, when the engine is installed, the valve is attached to the aircraft structure.

**Engine Cooling, Pressure Balancing and Sealing**

Air is bled from the main compressor to cool the turbine rotor discs, to supply air to the turbine and compressor balance pistons and to pressurise the bearing seals (with the exception of the main compressor inlet bearing).

The air to cool the turbine discs and supply the turbine balance piston is tapped from the diffuser after the main compressor, and passes into an annulus in the main support plate and to the turbine through two pipes. From the collecting

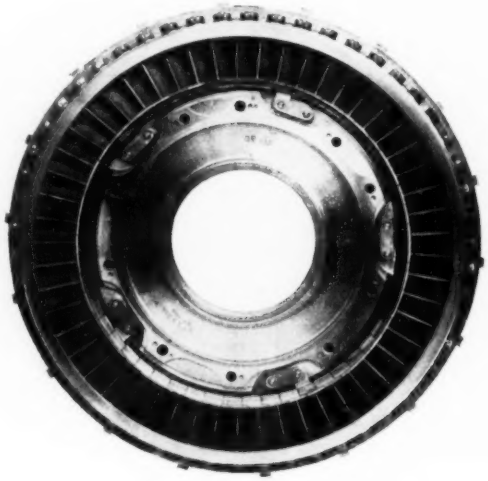


*Fig.* 15.—*Stage* 2 *turbine nozzle assembly*

annulus in the turbine the air flows to the balance piston chamber where it divides, a proportion passing through a seal and up the front face of stage 1 disc, and the remainder into the hollow shaft and to the other disc faces. In passing up the disc faces the air flows through scrolls attached to the seal plate, which in effect lengthen the path of the air and thus enhance the cooling.

*Fig. 16.—Auxiliary compressor components*

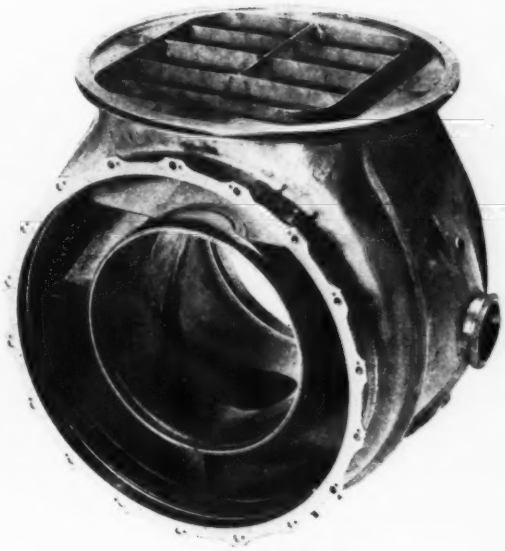


*Fig. 17.—Collector*

To pressurise the bearing seals, air is taken externally through a pipe and filter from stage 6 of the main compressor. Tappings from the pipe running on the outside of the engine are made at the appropriate places to supply each bearing. Spill air from the bearing seals is allowed to escape through the hollow auxiliary compressor shaft, where all oil vapour which may be contained in the air is centrifuged out and therefore retained in the engine.

Cooling air for the rotor head is taken from the same source through a non-return valve of the unbalanced butterfly type. The non-return valve is necessary to prevent a reversal of flow in the event of one engine being stopped in a multi-engined installation.

From stage 9 of the compressor a further tapping is made, by which air passes forward internally through a hole in the discs, similar to the bolt holes, to pressurise the main compressor balance chamber at the compressor inlet.

**Accessories**

The engine accessories are mounted on the front

*Fig. 18.—Two-way non-throttling valve*

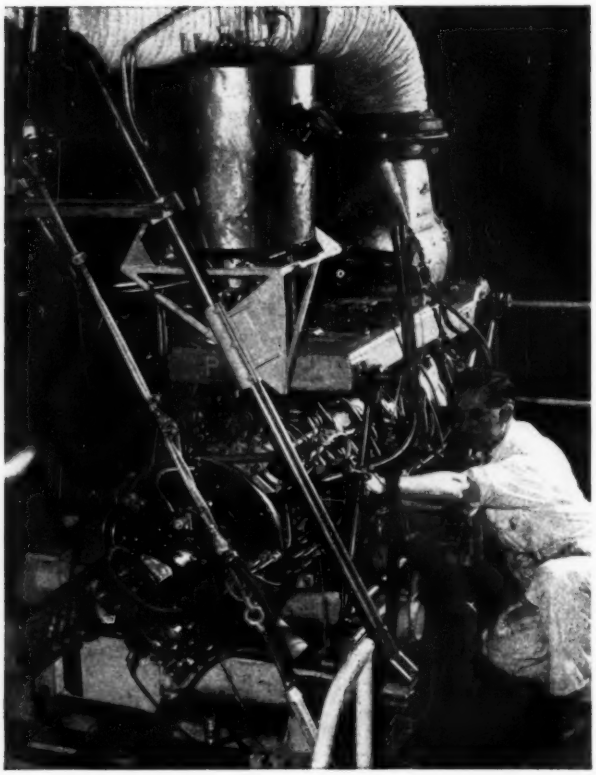


*Fig. 19.—A Napier 'Oryx' engine on the test rig*

of the main compressor inlet casing and are driven through a gearbox and quill shaft by the compressor shaft. The accessories comprise a fuel pump, a combined oil pressure pump and three-bank scavenge pump, and a tacho-generator. A drive is also provided for an engine synchronisation unit.

A Rotax electric starter, also situated in front of the main compressor, is mounted co-axially with the compressor and provides a direct drive on to the compressor shaft.

**Control**

Control of the engine is effected by a single lever operating a Napier fuel metering unit which automatically compensates for changes in ambient pressure and temperature conditions. An overspeed governor and a fixed-datum turbine inlet temperature control are included. Fuel is supplied by a Lucas fixed-stroke plunger pump.

An inlet guide-vane control which is responsive to engine speed is also fitted.

Control of the starting butterfly valve and the two-position non-throttling valve is manual. With a twin engine installation in which both engines deliver to a common duct, the manual control of the two-position valve may be overridden by a speed-sensing unit when the engines are not running at synchronised speed.

**Lubrication**

Dry sump lubrication is used, with oil cooler and oil tank. The rotary positive-displacement type pressure pump delivers oil at 150 p.s.i., which is restricted to maintain an engine oil pressure of 80 p.s.i. and a pressure of 135 p.s.i. in the non-throttling valve servo-mechanism reservoir. The oil filter is contained within the pump housing.

Each of the pumps comprising the three-bank scavenge pump is divided into two, so that independent scavenging is provided for each of the six main engine bearings.

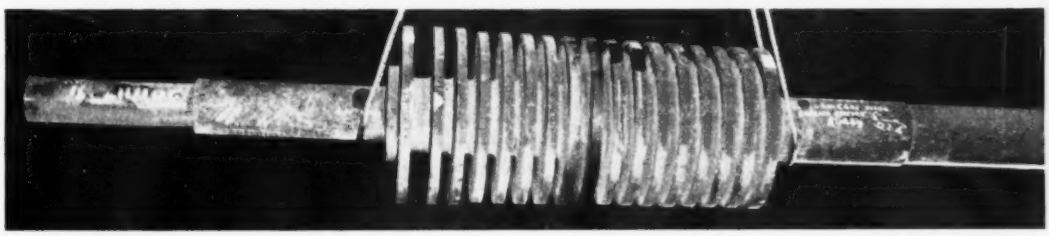
# *Metallurgical Features of Modern Steam Turbines and Alternators*

By F. BUCKLEY, B.Sc., F.I.M., Chief Metallurgist.

*This article is essentially a reproduction of the paper presented by the author on 26th January 1955 to the Thermal Section of the Canadian Electrical Association during the annual convention at Niagara Falls, Ontario, and published in the "Engineering Journal" of the Engineering Institute of Canada in July 1955.*

THE MAIN PURPOSE of this article is to give some idea of the methods by which the metallurgist and his associates have faced up to the difficult task of keeping pace with the designers of steam turbines and alternators.

The achievements of the designers during the past 30 to 40 years can be judged by the fact that individual sets having outputs in excess of 200 MW are now contemplated, steam temperatures have attained the level of 1,150°F, and pressures up to 5,000 lb/sq in are to be employed. These developments have necessitated large physical changes in the dimensions of the major components such as castings and forgings, resulting in pronounced manufacturing difficulties, and in addition the materials themselves have had to be entirely remodelled and many new alloys evolved.



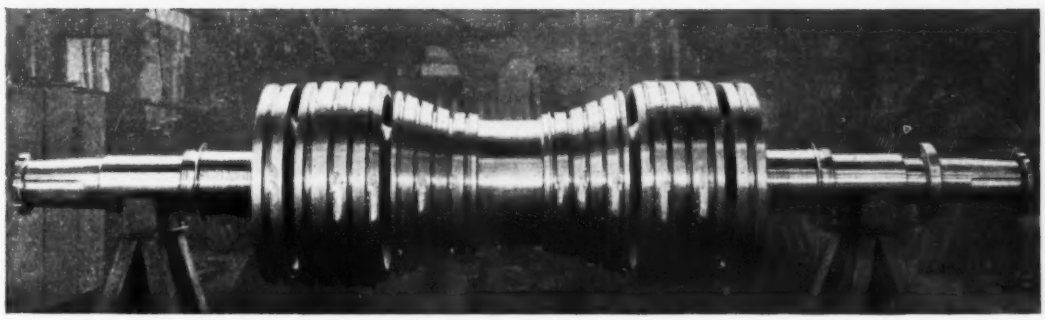
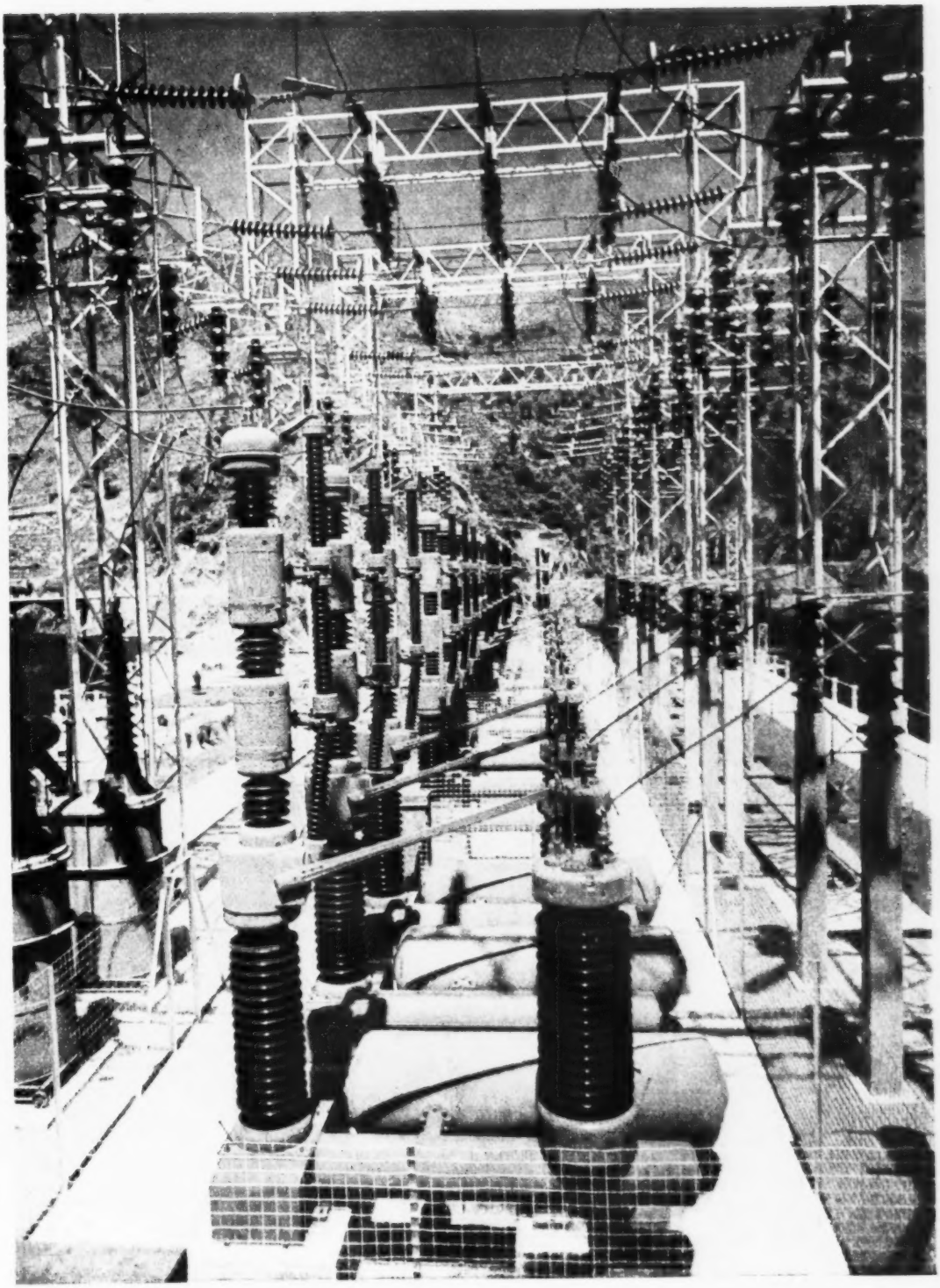


*Fig. 1 and 2.—Examples of early steam turbine rotors machined from solid steel forgings*

*This outdoor switching station at the Ponte Novo Power Station of the Saltos del Sil S.A., Spain, contains five* 165 *kV* 3,500 *MVA* ' *English*



*Electric' air-blast circuit-breakers controlling three 16,000 kVA generator transformer circuits and two circuits feeding into the Spanish grid system*

*This 80,000 kVA 230/115 kV three-phase transformer, being installed at the Folsom Dam o*
*supplied or being built by The English Electric Company for the United States of Am*
*Administration, and the St. L*

*n Dam on the Sacramento River in California, is the first of a number, totalling 1¾ million kVA, tes of America. Others are for the City of Seattle, Chief Joseph Dam, Bonneville Power d the St. Lawrence Seaway project*

These alloys have been designed not only from the point of view of accommodating the higher stresses and loads at normal and slightly elevated temperatures, but compositions have had to be evolved for the higher temperature conditions under which the metal is no longer able to support relatively low stresses without undergoing a permanent deformation. Accurate forecasts and allowances have therefore to be made by the designer so that the total amount of deformation or creep likely to occur during the life of the turbine is within the limits of service conditions.

It is obvious that as a result of these trends every component, either static or moving, has had to receive the most careful attention, and whilst it is not possible in a limited space to deal with all of them comprehensively, it is felt that a careful consideration of the most important items will be the best way of illustrating the improvements as a whole. For this purpose no better example can be selected than one of the most highly stressed major components in the whole assembly, namely, the rotors.

## ROTOR FORGINGS

Turbine rotors were originally built up of several parts which were joined by a combination of bolts, shrinkage or large threads ; the early 'twenties saw the advent of the solid steel rotors with discs gashed from a solid steel forging (Figs. 1 and 2). Early rotors of this type were universally made in plain carbon steel, being used at temperatures below those at which creep becomes a dominant factor and being of such a size and stressed to such levels that unalloyed steel was perfectly satisfactory. However, with the increasing output of the machines and consequent higher stress levels from the larger blading and rotor diameters, it became progressively necessary to stiffen-up the steels and increase the physical characteristics by alloy additions such as molybdenum, nickel and chromium.

In comparison with the plain carbon steel rotors of about 36 inches diameter, giving test results in the vicinity of 80,000 lb/sq in ultimate strength and 42,500 lb/sq in yield, there are now available rotor sizes up to 54 inches diameter in chromium molybdenum steel which will give ultimate strengths of 100,000 lb/sq in and ·2% proof stress in excess of 74,000 lb/sq in. The manufacturing difficulties and care necessary for the successful production of forgings of this type bear no relationship to those encountered in the forging of carbon steel rotors. Whilst still prone to all the complaints inherited from the ingot state such as segregation, inclusions, corner weakness, etc., these alloy steels demand the most careful attention at all stages of melting, forging and in particular heat treatment.

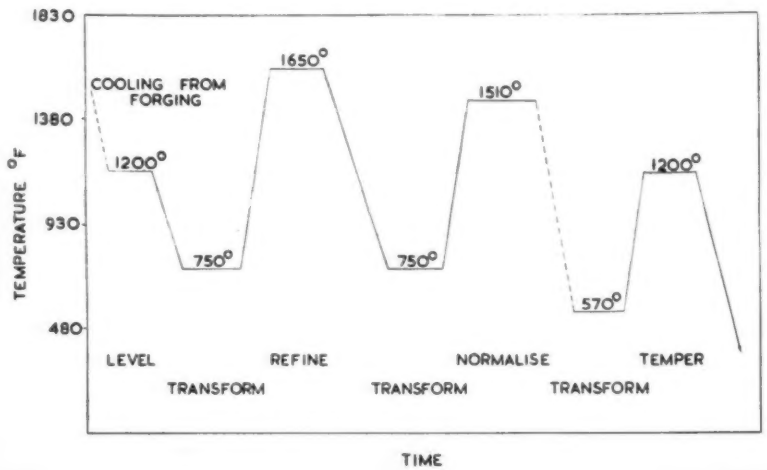



*Fig. 3.—Heat-treatment cycle*

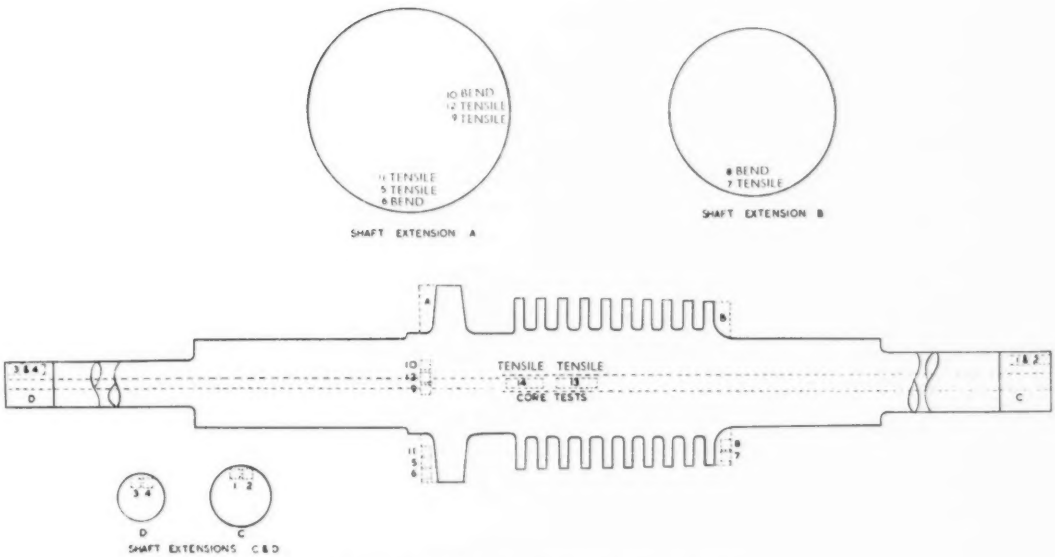



*Fig. 4.—Locations for physical tests on rotor*

The danger is the presence of hair-line cracks or 'snowflakes' which, buried deep in the forging and unsuspected with the normal visual and magnetic inspection methods, can, if undetected, cause catastrophic failure of the forging in service. The successful elimination of these defects has not only resulted in improvement of steel making and forging practice but has also revolutionised inspection techniques as applied to these rotors. These cracks are probably due to the joint effect of hydrogen in the steel coupled with internal stresses due to transformation changes and thermal gradients. Great care must therefore be taken to keep the hydrogen content of the steel at a minimum, particularly during the melting process, and internal stresses and thermal gradients must be minimised by prolonged manipulation at high temperatures. Immediately after forging, therefore, and whilst still at a high temperature the forging must be given an elaborate cycle of heating and cooling between approximately 1,650°F and 570°F (Fig. 3).

In addition to these precautionary heat treatments it is necessary to subject the forgings to a final hardening and tempering treatment to effect the highest physical properties, which must be as uniform as possible throughout the section thickness. This process may consist of rapid air cooling from a temperature above the change point, followed by tempering, or, as is practised more in Europe, the whole forging may be oil quenched followed again by a tempering treatment. There is a certain amount of opposition to the drastic oil quenching, due to the fear of heavy resultant internal stresses which may prejudice the service conditions, but if the tempering is carried out with sufficient care it would appear from experience that there is little to fear on this account.

## Inspection

Inspection of the resultant rotors can be classified into four main branches, not all of which can yet be the subject of official specifications covering acceptance clauses, namely (1) external physical tests, (2) bore tests, (3) ultrasonic examination, and (4) stability.

### *Physical Tests*

Physical tests taken from the three principal directions, longitudinal, tangential and radial, provide an indication of the general quality and treatment of the material (Fig. 4). The position

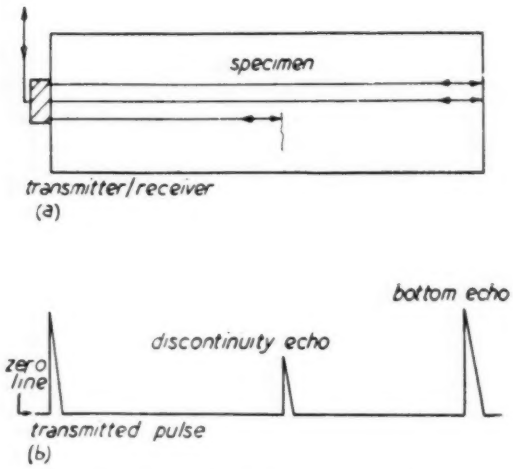



*Fig. 5.—Principle of ultrasonic examination*

of testing will, in general, correspond to the outside of the forging and so will not necessarily be a true representation of the material at the centre of the forging. A compromise is possible in this respect by selecting a bore test from a trepanned core, or alternatively, and particularly applicable to alternator forgings, trepanning radially into the body. Careful checks of the material from the outside to the centre can then be made.

*Bore Tests*

By the provision of a bore in the forging it is possible to cover the double purpose of inspection and assistance in the removal of central weakness in the forging, the bore being afterwards examined with a magnifying boroscope. It is also common practice to magnaflux the bores prior to this final inspection. The criterion of acceptance is the complete removal of all defects in the main barrel portion of the forging, local chambering being permissible, however, at the discretion of the designers. It is permissible to allow minor defects in the shaft extensions provided these are scattered inclusions and not related to any crack system. Directly as a result of the wider application of ultrasonic examination, which is next described, certain manufacturers are tending to leave the bores of large rotors solid.

*Ultrasonic Examination*

Although clauses covering acceptance based on ultrasonic examination are difficult to write into a specification at this stage, it is assumed by suppliers and users of major shafts that this type of inspection will be applied. The principles involved are fairly well known but can be summarised as follows.

Certain crystals such as quartz or barium titanate when excited by high frequency currents vibrate at a very high frequency, and if in contact with steel, for example, the vibrations are transmitted to the material, reflected back at the base and can be picked up by the same crystal. The echoes so produced are received and reconverted into electrical impulses which are registered on a cathode ray oscillograph (Figs. 5 and 6). The oscillograph indicates two or more peaks on the scanning trace, the first being produced when the transmitted wave enters the steel, and the second when the reflected wave leaves. If, however, a discontinuity is encountered, the vibrations are mostly reflected back and a third peak, intermediate to the first two, is obtained, the position on the oscillograph roughly corresponding to the depth from the surface. In addition, the seriousness of a flaw will be judged by the relative diminution of the bottom echo.

It is necessary to apply ultrasonic examination

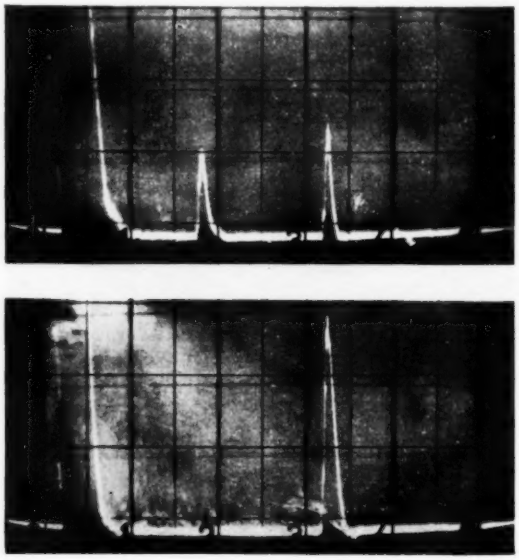


*Fig. 6.—Oscillograms from ultrasonic examination*

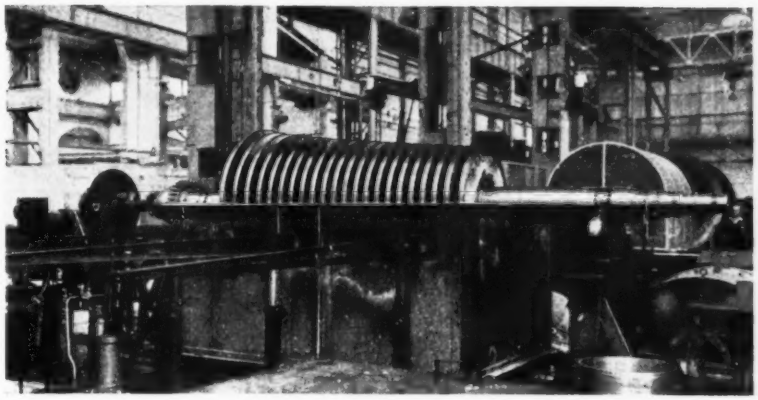


*Fig. 7.—Furnace for testing the thermal stability of rotors*

at various stages in the manufacture of the forging since reflections can be obtained from metallurgical features which are not in themselves harmful and which may diminish or disappear during the heat treatment.

*Stability*

The rotor must be of the correct material, heat treated to give the necessary physical properties, free from internal defects as revealed by visual, magnetic and ultrasonic examination, and free from internal stresses which unless corrected may lead to distortion of the rotor in service. It must also be thermally stable, i.e. it must, on heating up, remain true and not run eccentrically at temperature.

These two dangerous tendencies are checked by subjecting the rotors to special tests in thermal stability furnaces, one of which is illustrated in Fig. 7. The forging is rotated on steadies and driven electrically through a universal coupling at about 2 r.p.m. in a furnace which may be either gas or electrically heated to a maximum of 1,200°F. Three levers rest against the bottom part of the shaft at the two ends and midway position, any movement of the shaft being magnified four times ; a typical record of the movement of a shaft is shown in Fig. 8.

If there are internal stresses in the shaft the tendency is for the deflection at temperature to be partially permanent. In the case of thermal instability, however, the forging will run eccentrically at temperature, returning to its normal position when cold. This condition is difficult to correct since it means that the material of one side

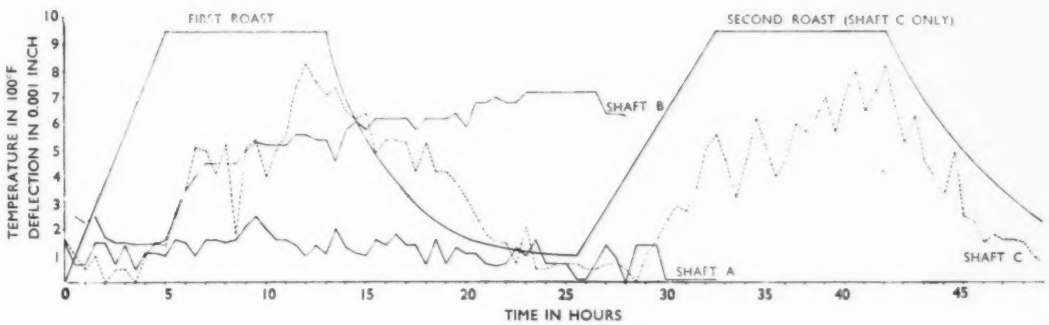



*Fig. 8.—Record of shaft movement during stability tests*

of the rotor has a different coefficient of expansion to that of the other, this difference being due to a variation of structure rather than of composition. It is possible for differential cooling rates during the heat treatment operation to account for this variation in structure, and very minor differences in the coefficient of expansion are sufficient to cause the rotor to run eccentrically at temperature. The eccentricity permissible at a temperature of 1,050° is definitely less than ·001 inch, and with careful heat treatment, particularly with the wider application of vertical quenching and tempering during which the forging is rotated, it is possible to get uniform rotors well within this limit.

### Bends in Rotors

The type of test just described also becomes of major importance when applied to rotors which have been bent in service and which have been

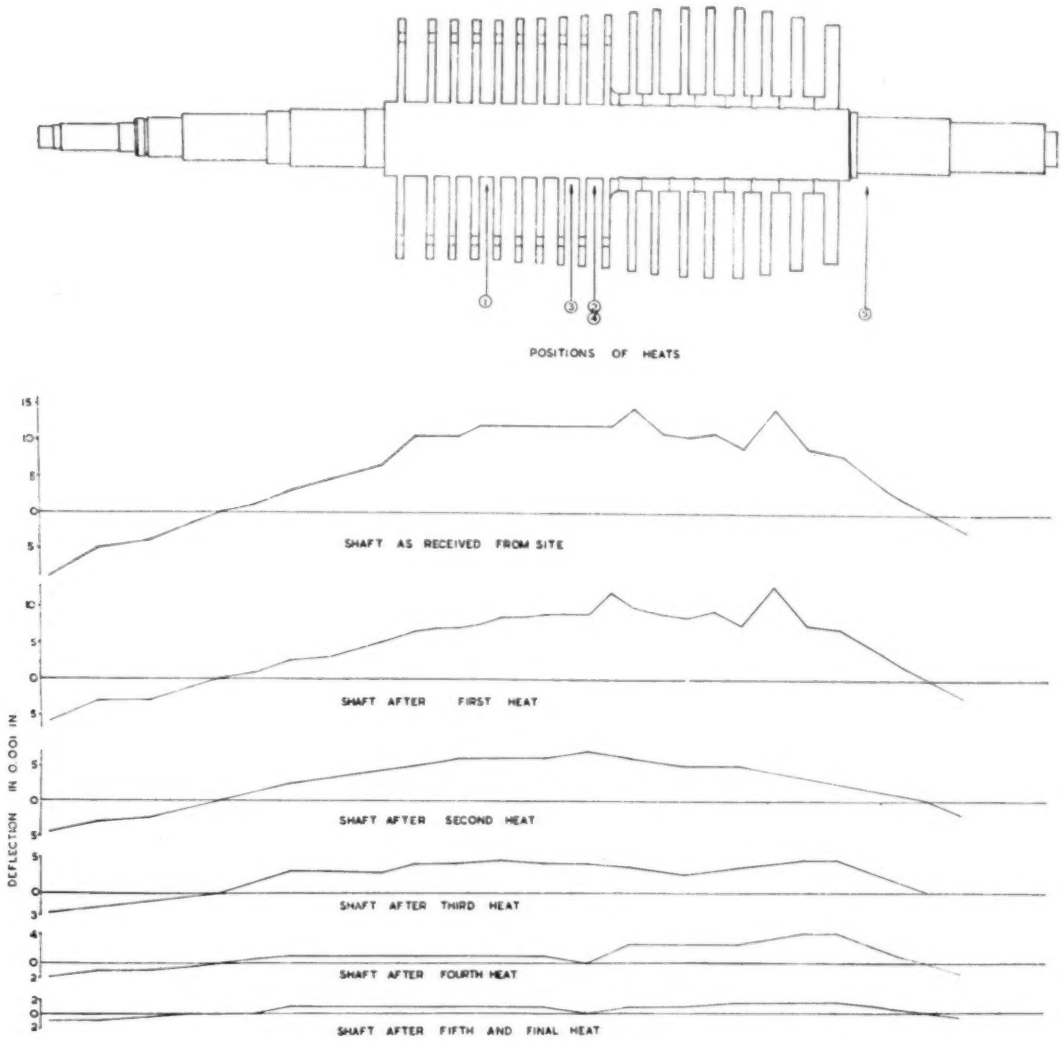

POSITIONS OF HEATS
DEFLECTION IN 0·001 IN
SHAFT AS RECEIVED FROM SITE
SHAFT AFTER FIRST HEAT
SHAFT AFTER SECOND HEAT
SHAFT AFTER THIRD HEAT
SHAFT AFTER FOURTH HEAT
SHAFT AFTER FIFTH AND FINAL HEAT

*Fig. 9.—Results from correction of bent shafts by heat treatment*

corrected (Fig. 9). The bend is usually associated with pronounced rubbing of the shaft against the glands, and it should be noted that the hump of the bend is diametrically opposite the scored part of the shaft ; in other words, the final bend is contrary to the bend occurring during the rubbing operation. This is because the scored part of the shaft rapidly attains a very high temperature and becomes plastic, yielding locally due to the compressive stresses of the neighbouring zones coupled with the restraining action of the glands themselves. Thus, on cooling, this side of the shaft contracts slightly and the final bend is found to be in the reverse direction.

Correction of the fault is therefore carried out by heating the shaft locally and rapidly at the apex of the hump, and repeating in reverse the same process which produced the original bend. On the application of the heat the bend increases, the local

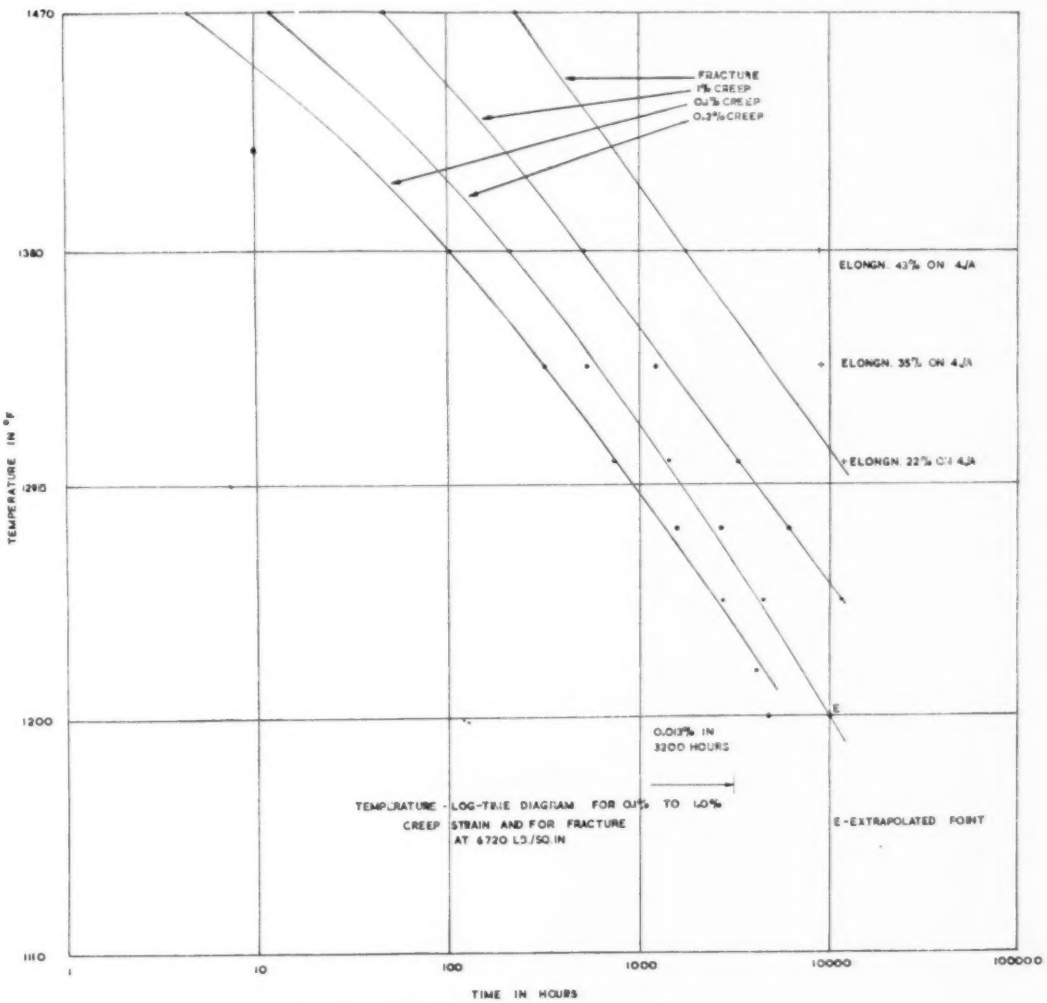



*Fig. 10.—Results of creep tests at increasing temperatures*

area affected is rapidly brought into a plastic state at a temperature in excess of 1,400°F, and this zone again is slightly deformed by the nearby retaining stresses so that in cooling the shaft tends to straighten.

It may not be possible to straighten in one operation, but by successive and carefully applied heats the bend can be completely corrected. The final heat is always followed by treatment in the thermal stability test rig when it is usually found that a further slight movement of the shaft occurs in the original bend direction, an effect which can be allowed for by slightly overcorrecting the deflection. The final treatment confirms the effectiveness of the straightening and minimises internal stresses.

**Creep**

As already mentioned, the combined effects of heavier stresses and larger components have necessitated a wide adoption, for medium and low temperatures, of alloy steels. Nickel, chromium and molybdenum are the normal addition elements in varying amounts, and the resultant steels possess the necessary yield and strength characteristics in the heavy sections now being used. Acceptance of these materials and the necessary data for design purposes can be adequately gauged from physical tests at room temperature, provided these are taken from positions representative of the components involved.

Above temperatures of approximately 850°F, however, the whole question of creep must be taken into consideration, the material in this case being largely non-elastic and a steady stress, a fraction of the normal low-temperature yield stress, may produce a permanent deformation of a magnitude which is a function of temperature and time. The designer must therefore have knowledge of the long-time behaviour of the materials he is using and must select stress levels which, in the life of the turbine, give deformation which will not be dangerous. The permissible deformation will vary with the service duty, but for such highly stressed important components as rotors, etc., it is not permissible to allow deformation higher than 0·1 to 0·2% in 100,000 to 150,000 hours.

It will be appreciated that the accurate forecasting of the deformation behaviour of a turbine component after a period of 12½ years has, in the past, had to be made on the results of creep tests running for a fraction of that time, and controversies regarding the reliability of any given system of extrapolation have been loud and long.

One method which has been used extensively with a fair degree of safety comprises the selection of a stress which has a relationship to the working stress and at which creep tests are carried out at increasing temperatures to a maximum considerably above the working temperature. From the resultant creep curves the times required to give say, 0·1% deformation or even rupture are plotted logarithmically against the temperature as shown in Fig. 10. A certain amount of extrapolation has been used with this method and on the whole, and from the results of confirmatory long-term tests, such forecasts do not appear to have been very wide of the mark.

Happily many actual long-term tests started several years ago as an extension of jet and gas turbine testing programmes, are just beginning to come of age and are proving the accuracy or otherwise of the estimated life values. In addition, test pieces taken from actual rotors are under test many thousands of hours in advance of service conditions. These will act as valuable guides to the behaviour of the components in practice, and verify the reliability of creep tests taken from small samples.

From all this data, and taking into consideration in addition the whole range of high temperature components, it would appear that molybdenum or chromium molybdenum steels are effective for temperatures up to 950°F. From this temperature up to 1,050°F the molybdenum vanadium steels with additions of chromium and tungsten can be relied on, provided that in the highest ranges the stress levels are kept down to 4,000 lb/sq in. Above this temperature the further important factor of surface oxidation must be taken into consideration, and considerable chromium percentages must be added to the steel to combat this effect. With contents of about 13% it would appear that the chromium steels of the ferritic type have a useful life up to 1,100°F and perhaps even 1,150°F. For the highest temperatures the only

possibility is the austenitic steels, 18% chromium, 8% nickel with 1% columbium.

**Joints Between Materials**

Although it would appear from the foregoing that there is a smooth gradation of materials up to the maximum temperature, the change from a ferritic to an austenitic steel is quite marked. The two materials have different coefficients of expansion, the austenitics' being 50% higher than the ferritics'; they also have varying heat transfer rates, and therefore junctions between the two materials inevitably lead to major complications.

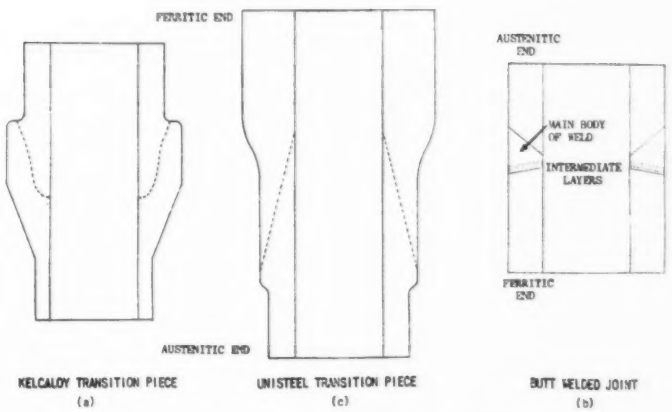



*Fig. 11.—Specialised joints developed to accommodate cyclic thermal stresses*

In many high temperature turbo-alternator sets the superior creep strength of austenitic materials can mean lighter sections for a given duty, which in the case of pipework means greater flexibility. A major problem therefore develops at the positions where these austenitic parts join the main ferritic components such as the stop valve or turbine casing; the connections must be capable of accommodating the cyclic stresses due to temperature variations applied to the two materials of vastly different physical characteristics.

It is obvious that these positions must receive careful attention, and the specialised joints which have been evolved for this purpose can be classified under the following three headings (Fig. 11).

(a) *Kellogg Joint*

A heavy stainless deposit is formed on a ferritic base, being built up in such a manner as to yield a scarfed joint; the stepped shape is designed to prevent a feather edge at the outside junctions. Assemblies of this type have been in service for periods of six to seven years.

(b) *Butt Weld*

Butt welds between austenitic and ferritic materials have been used employing austenitic welds as the filler material and utilising special techniques to prevent carbon migration from the ferritic to austenitic material. If this migration is allowed to proceed, it leaves an area adjacent to the actual weld which is readily attacked and may be the starting zone of serious cracking.

(c) *Unisteel Joint*

By this method a composite billet made up of austenitic and ferritic materials is extruded over a mandrel to produce a scarfed joint, a layer of nickel between the two materials preventing carbon migration. This is a new joint which is just coming into use but which shows every sign of having a promising future.

**Austenitic Materials**

Large components in austenitics have not been used to any great extent in turbines employing steam temperatures in the 1,050°F-1,100°F range, but more stringent conditions may see an extension of these materials to the major components. In this connection the experience gained in gas turbine practice will be of considerable value.

The use of these austenitic materials described so far has been in their high temperature applications. When considered for low temperature use, particularly in alternators, where their non-magnetic properties are of major importance, one drawback applicable to forgings of any appreciable size is their poor elastic properties. The usual austenitic compositions are relatively soft with low yield points which, for highly stressed components,

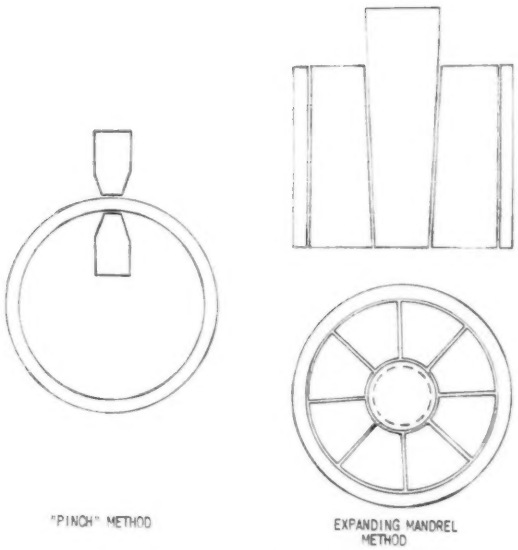



*Fig. 12.—Alternative methods of cold-working end-bells*

can only be increased by pronounced cold working.

An example is the non-magnetic end-coil retaining rings for alternators. These hollow cylinders are manufactured by one of two methods. Initially in both cases the forging is first upset, punched, reforged and then machined, quenched in water which leaves it in its softest condition and then subjected to one of the following two heavy cold working processes (Fig. 12).

(*a*) In the first method the rings are pressed locally between an internal mandrel and a press head in a series of axial steps until the whole circumference is treated as uniformly as possible.

(*b*) In the second method the work hardening effect is produced by an internal expanding mandrel which is made up of segments operating independently and governed by radial 'T' slots. The eight segments are tapered in the centre to allow the entrance of a taper mandrel which is driven in by a press, thus forcing the segments outwards and expanding the ring. In a further endeavour to attain uniformity in the forging, the ring is rotated slowly and intermittently during the operation.

It would appear that method (*b*) tends to give an end ring with the most uniform physical properties, and yield points of approximately 127,000 lb/sq in with ultimate strengths of 150,000 lb/sq in are obtainable.

It must be appreciated that this cold working process involves an increase in diameter of the forging of approximately 30% and an increase in hardness up to 350 Brinell. Great care has therefore to be taken to avoid localised work-hardening effects which may completely rob the material of any remaining ductility or ability to accommodate by plastic deformation any overstress. The drilling of ventilation holes for example, unless carried out with extraordinary care, may give this additional work-hardening effect, and as the holes also act as stress raisers it is advisable to eliminate them even at the risk of loss in cooling efficiency. This step was taken in the case of the appropriate products of the English Electric Company as long ago as 1950, as the result of experience and research developments. The material in the highly stressed state is also susceptible to stress corrosion effects, and the most careful attention to storage, protection during manufacture and during actual running is fully justified.

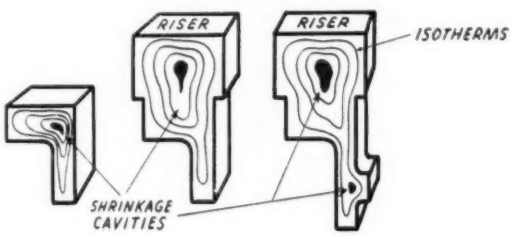



*Fig. 13.—Formation of shrinkage cavities in castings*

## CASTINGS

The discussion so far has dealt generally with forgings. Turning next to castings in steam turbine assemblies, it is general practice to use cast iron for such purposes as casings and exhaust chambers for maximum temperatures of 450°F. This figure,

however, has been increased in the United States to 650°F for the improved fine graphite structures such as Meehanite, and it is possible that other countries will tend to increase the somewhat conservative figure of 450°F. Although ductile iron has not been used to any great extent in steam turbine practice it is possible that it could have a useful field of application for castings subjected to intermediate temperatures, since there is evidence that the growth and heat resisting characteristics of nodular structures are better than those of the normal cast irons.

Considering steel castings, compositions in general coincide with those adopted in forgings, care being taken to keep carbon contents low for welding purposes. For any given composition the creep value of a casting, based on the results of actual tests, is rather lower than but of the same order as those attained with forgings or bar material. Without minimising in any way the importance of composition as applied to steel castings, it should be clearly understood that the most important feature is soundness, and it is this factor which completely overshadows everything else.

**Collaboration between Designer and Founder**

Assembling the components of a large machine such as a steam turbine can occupy a period of months, necessitating the co-ordination of finished parts to a strict time schedule which can be completely disorganised by prolonged rectifications and possible rejections at a late stage of manufacture. Unfortunately, no component is likely to give more trouble in this respect than a steel casting. The reasons for these difficulties will be appreciated when it is remembered that the casting process consists of pouring a liquid of limited fluidity, and high shrinkage characteristics both in the liquid and solid states, into a friable sand mass of dubious mechanical properties. Further, the latter offers major resistances to the free contraction of the castings at temperatures corresponding to minimum strength conditions of the steel.

Success, therefore, can only be achieved if the design readily responds to the stringent conditions imposed during the casting and cooling processes. This calls for active and intense collaboration between the designer and the foundryman. It should be remembered that the contraction of liquid steel amounts to 1·6% for every 212°F drop in temperature, and the contraction at the moment of solidification is 3·5% of the subsequent volume at room temperature, facts which are typified in Fig. 13. In any steel castings, therefore, cavities with or without hot tears will inevitably occur unless the cooling conditions are such that the last part of the metal to ' freeze ' is outside the casting and in the riser. In addition, after solidification there is a great danger of hot cracking or the formation of tears at a high temperature unless the component parts are free to contract with a minimum of interference.

It is vital, therefore, that all concerned should be aware of the method of moulding so that some

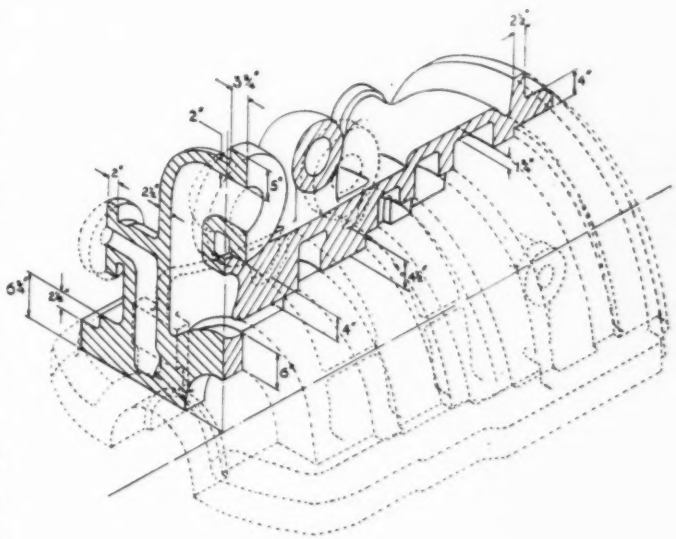
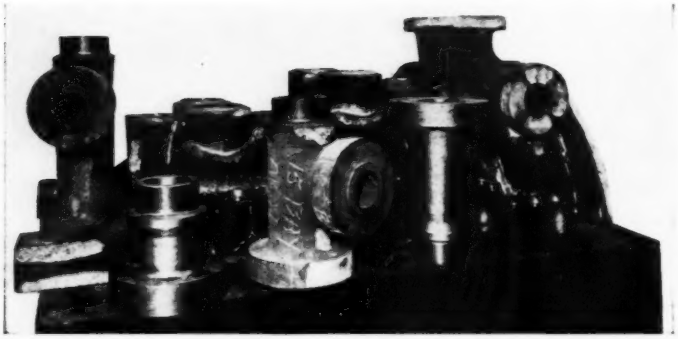



*Fig. 14.—A turbine casing, illustrating the complexity of casting problems*



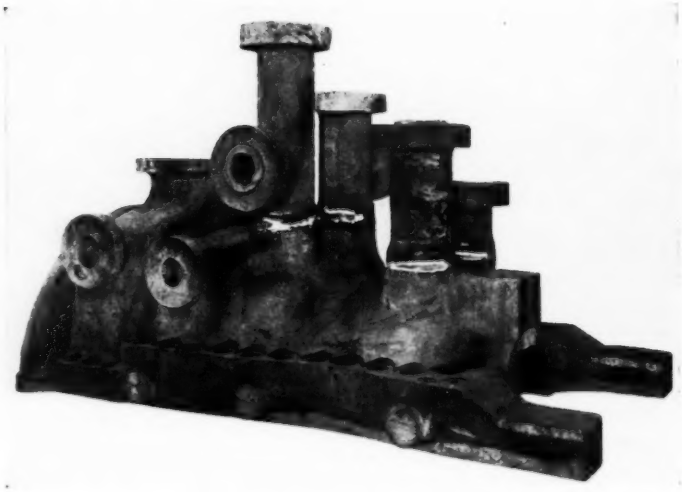


*Fig.* 15 *and* 16.
*Examples of composite casting and welding construction, permitting the use of separate castings in different materials*

idea of the pattern of solidification can be formulated. By consideration of these details section thicknesses can sometimes be so arranged that solidification proceeds progressively from the positions furthest away from the riser, the last portion of the molten metal being in the riser itself. Unfortunately the number of castings which allow such forecasts to be made with any accuracy are very few, and a typical problem applying to a steam turbine casing is illustrated in Fig. 14. No matter which way this job is made there will be zones which will be most difficult to feed, and the utmost skill is called for from the foundryman regarding the positioning of risers and chills to accelerate cooling of isolated heavy sections. This is mainly a function of experience, and the successful production of a casting such as the one shown depends more often than not on a slow empirical build-up of ' know-how.'

The turbine designer can help in this respect by concentrating the manufacture of this type of complicated work into a minimum number of foundries for a sufficient period of time to enable the techniques to be acquired. In addition it is necessary to assist the foundryman by simplifying the construction and incorporating the composite welded and cast structure where possible.

**Composite Structures**

The ' breakdown ' of a composite structure into component parts calls for the utmost care on the part of the designer to avoid such undesirable features as heavy stress concentrations in the vicinity of the welds. This breakdown simplifies the pattern construction, enables the mode of solidification of the individual units to be forecast and facilitates the finishing operations, since considerable machining of the components is possible with a consequent saving in heavy machining time.

The composite casting techniques can be illustrated by a comparison of Figs. 15 and 16 with Fig. 14. In these first two illustrations all the branch pipes and auxiliary connections are produced separately, partly machined and directly butt-welded into position. In addition, this type of construction allows the employment and welding into position of highly alloyed components with specialised properties such as good creep

resistance, whilst the main casting may be of a lower alloy content.

Fig. 17 illustrates this trend, the nozzle box being subjected to the maximum steam conditions of 1,050°F and 1,500 lb/sq in. This is a 3% chromium, molybdenum, vanadium, tungsten alloy, whilst the main casting is a ½% molybdenum, vanadium alloy. Similar assemblies have been used in which the nozzle box is austenitic, additional modifications in this case being necessary to accommodate the differential expansion characteristics.

**Inspection**

Inspection has an important part to play, since it is vital with steel castings that the complete lay-out and summation of defects should be ascertained as soon as possible in the life history of the component. The following methods are adopted.

(a) *Magnetic Crack Detection*

This is, of course, based on the interruption caused in a magnetic field by defects such as hot tears, shrinkage cavities and allied phenomena, and in the same general class of inspection can be included the use of penetrating dyes, etc.

(b) *X- and Gamma-Radiography*

These play an important rôle not only in the exploration of pilot castings in the foundry but also in routine examination of specialised zones in large castings.

Although portable X-ray equipment is available in sizes up to 250 kV, allowing effective examination of material 2½ inches thick, the larger sets of 400 kV and upwards, suitable for thicknesses of 4½ to 7 inches and over, necessitate permanent installations with protective measures for the operators. For greater thicknesses, examination of heavy sections with rays generated by orbital accelerators is now being employed ; particles are accelerated to high energies, and liberate X-rays after bombarding targets.

The energy from X-rays generated at medium voltages up to 400 kV is relatively easily absorbed, and plates of high contrast are obtained provided sections of approximately the same thickness are examined on the one plate. Where marked changes of section are involved, precautions are necessary against loss of detail at the edges, but subject to these precautions a higher degree of contrast can be obtained than with gamma-radiography.

The chief sources of gamma-rays are radium, radon, and the radioactive isotopes. Radium is obtained from natural sources. Radon is a gas, the product of spontaneous disintegration of radium ; this gas is absorbed in activated charcoal within a glass tube and, in common with all these materials, emits gamma rays at a rate decreasing with time. The principal radioactive isotopes are those of iridium and cobalt.

With the exception of iridium, radiation from all these materials is very similar. They have a low absorption capacity and no special precautions with variable thicknesses are necessary. Iridium $^{192}$,

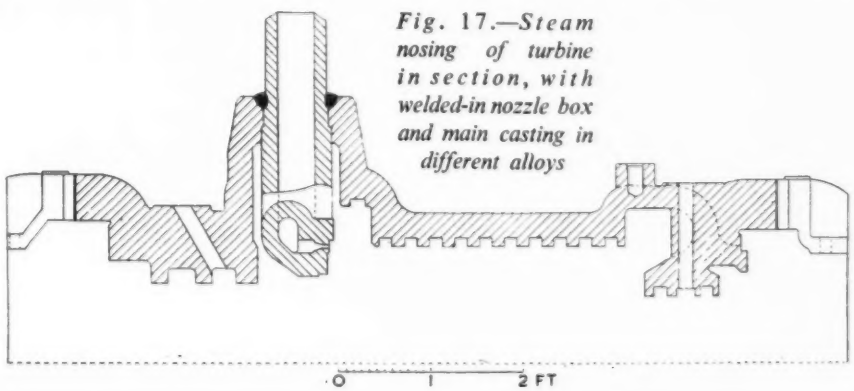



*Fig. 17.—Steam nosing of turbine in section, with welded-in nozzle box and main casting in different alloys*

which has a low gamma-ray emission, yields relatively high contrasts and is suitable for thicknesses up to 2 inches. Cobalt $^{60}$ and radon are applicable to greater thicknesses.

With regard to radiographic standards, such as the A.S.T.M. Standards, the main point to emphasize is that a clear understanding is necessary at the commencement between the user and the founder as to the use of these and the areas and zones to which they are to apply. Unfortunately in so many steam turbine castings there is difficulty in interpreting X-radiographs, particularly when taken in the vicinity of the junctions which are the most likely sources of dangerous defects such as hot tears, etc. (Fig. 18). Great care is therefore necessary, since indications may be isolated defects or the outcrops of far more dangerous defects, and it is only a clear understanding of the solidification procedure which enables a clear analysis to be made.

(c) *Acid Pickling*

Pickling in hot sulphuric acid with restrainers is a particularly good method of showing hot cracking zones, and has the additional advantage of removing burnt-on sand defects which may otherwise come adrift and damage turbine blading. Objections have been raised to this process by some founders on the grounds that the hydrogen liberated may aggravate the cracking, but these fears appear to be ill-founded providing the casting is heat treated before and after the operation.

(d) *Ultrasonic Examination*

This method of examination, as applied to castings for steam purposes which are usually of a complicated nature, has only limited application. Not only are there the difficulties associated with surface conditions but also the discrepancies inherent in castings of this type, which are of minor importance from the point of view of service duties but complicate the reflection patterns obtained in examination.

Identification and assessment of defects by any of these methods must be relative to the service duties, and if repairs are possible they usually involve complete removal of the defects followed by an agreed welding technique and corrective heat treatment.

*Fig.* 18.—*Steam turbine component, exemplifying the care necessary in interpreting X-radiography in the vicinity of junctions*

## OTHER METALLURGICAL FEATURES

Space permits only a brief reference to some other metallurgical features of both turbines and alternators. Subjects deserving more attention include the rotor windings of alternators and the steps taken to overcome copper shrinkage. This occurs in windings of large turbo-alternators which are subjected to shift working, and it is only by the introduction of copper alloys containing silver additions, which increase the creep strength and reduce the softening tendencies following cold working, that these difficulties have been overcome.

One further major problem in the utilisation of higher temperatures is that of metal-to-metal contact and the selection of surfaces with adequate sliding and anti-galling properties, with particular reference to valve components. Nitrided surfaces appear satisfactory up to 950°F, but above this it may be necessary to call upon much more complicated materials such as stellite and silicon

monel for bushes, and stainless materials for spindles.

The development of materials for condenser tubes could in itself provide the subject of an article illustrating the manner in which dezincification and impingement attacks have been, in the main, successfully overcome. Small arsenic additions to 70/29/1 Admiralty brass metals are effective in avoiding dezincification, and the development of aluminium brass 76/22/2 with arsenic additions has successfully eliminated impingement attack except in highly polluted waters. In addition, and coincidently, the cupro-nickels have been successfully developed for service in many difficult waters. These usually contain small percentages of iron and manganese, and although they have a higher all-round corrosion resistance than brass they have a lower thermal conductivity which must not be neglected. As a result of the shortage of nickel, new cupro-nickel alloys have been developed with approximately 10% of nickel coupled with 2% of iron. These have given good results in power stations where other materials have not proved adequate. There are cases where both cupro-nickel and aluminium brass have failed, and it may be that tin bronzes have a corrosion resistance which the other alloys do not possess ; however, considerable experimental work is being carried out on these materials.

**Conclusion**

The general trends of the methods by which the metallurgist, forgemaster and founder have been able to meet the demands of the turbine and alternator designers have been outlined. These demands are by no means static, and it is obvious that in the future even greater calls will be made on the technical skill of the producers of the major components. Happily there is a clearer understanding of the processes which control the occurrence of defects in both forgings and castings, and this fact gives confidence in the future production of the components for the higher duties which will be required. It should be remembered also that the techniques of inspection are improving, probably faster than those concerned directly with manufacture, and whilst this is a source of satisfaction to the turbine and alternator user, a heavier responsibility is placed on those concerned with the acceptance and manufacture of the materials involved.

# *A New Low-Oil-Volume Type of 33 kV Voltage Transformer and some Voltage Transformer Considerations*

By E. J. MELLOR, Instrument Transformer Engineer.

ENGLISH ELECTRIC 33 kV voltage transformers have given many years of satisfactory service, but it was felt that more compact units could be constructed by departing from the miniature power transformer type of design used in the past.

By employing a technique using oil impregnated cable paper for much of the major insulation, and by building the bushing as an integral part of the transformer, a very considerable reduction in size and oil content has been achieved in the new design described in this article. At the same time, improvements in the insulation and electromagnetic characteristics have been attained.

To give a better understanding of these points, some fundamental principles and requirements are discussed.

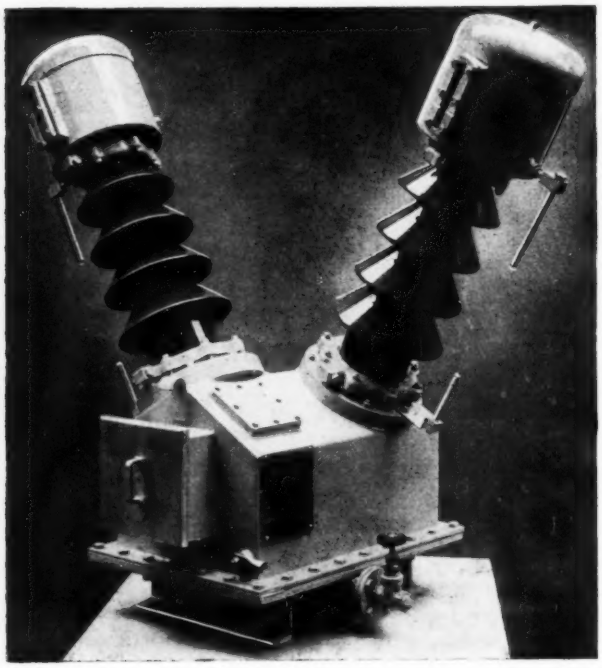


*Fig. 1—Single-phase line-to-line 33 kV low-oil-volume voltage transformer*

## CONSTRUCTION

Three types are available and are suitable for either indoor or outdoor use:—

(1) Three phase, 3 or 5-limb units.
(2) Single phase for line-to-line connection (Fig. 1).
(3) Single phase for line-to-earth connection.

While the single-phase type for line-to-line connection is described here, all types are constructed on the same principle using many common parts, e.g. bushing arrangement, coils, etc.

### Core

The core of high grade silicon steel is of the normal shell type construction having a three-stepped centre limb around which are mounted the low voltage and high voltage coils.

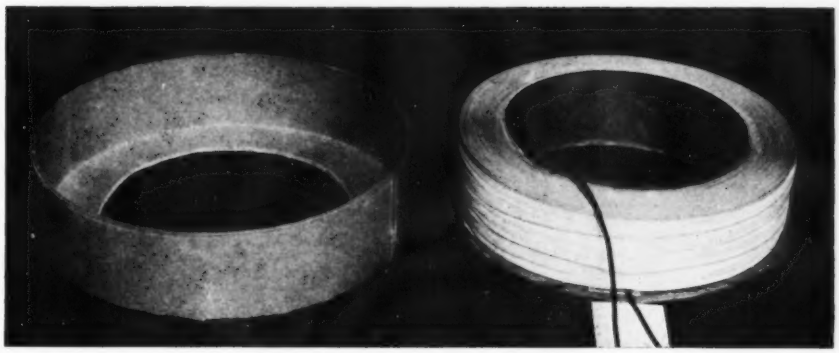


*Fig. 2—One of the four H.V. coils and pressboard box ring*

An angle iron frame clamps the core and supports the coil stack. Jacking bolts facilitate the rigid location of the coils.

**Windings and Insulation**

Cylindrical concentric spiral windings are assembled with the L.V. coils nearest to the core.

*Fig. 3—Pair of H.V. coils after insulation*

*Fig. 4—Complete core and coil assembly*

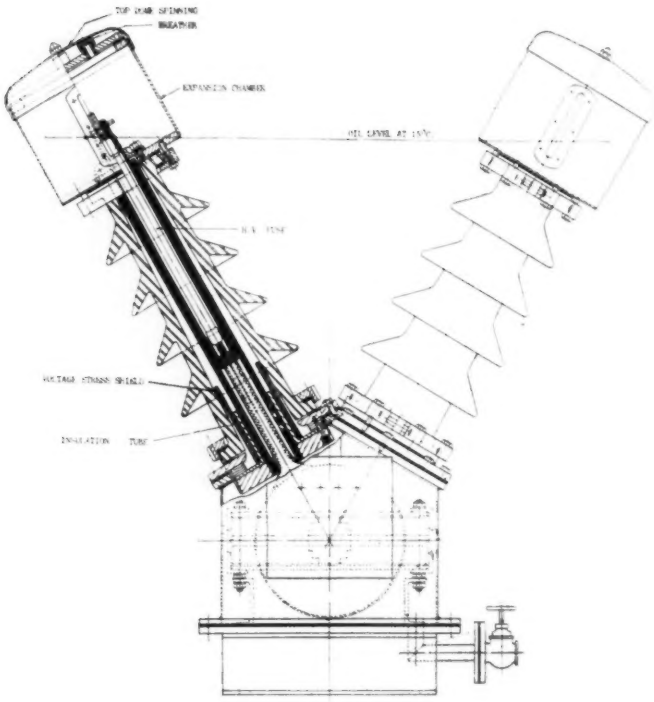


*Fig. 5—General arrangement of line-to-line voltage transformer*

Either one or two L.V. windings can be provided, and are wound on a bakelised paper tube which forms the insulation between the L.V. coils and the core.

Four H.V. coils connected in series are used, one of which is shown in Fig. 2. The coil of small gauge round wire is wound on a loose-petalled pressboard angle ring. When complete a pressboard box ring, also shown in Fig. 2, is placed over the coil. These two rings encase the coil, so that in addition to supplying some of the inter-coil insulation, adequate mechanical protection of the coil is provided.

Oil impregnated cable paper is used for the major insulation; coils are initially taped individually and finally in pairs. From each pair is brought a lead heavily insulated in such a manner that the insulation is an integral part of the coil (Fig. 3). The lead end is connected to a high voltage terminal in the expansion chamber. A complete core and coil assembly is shown in Fig. 4.

**High Voltage Bushings and Fuses**

The H.V. bushing arrangement is integrally constructed with the transformer (Figs. 1 and 5). It consists of an outdoor type porcelain casing, through which the taped H.V. lead is brought in insulating tubes. If required, an easily removable high voltage fuse can replace part of the taped lead (Fig. 5). A voltage stress shield is introduced at the bottom of the porcelain where the H.V. lead enters the metal tank.

The interior of the bushing is open to the tank, thus permitting oil in the bushing and the transformer tank to mingle.

The upper portion of the bushing acts as an oil expansion chamber. It is fitted with an oil gauge utilising prismatic glass to ensure clear oil level readings. Restricted breathing to the atmosphere is allowed via a small breather located under the top dome spinning. The latter gives complete protection from the weather for both breather and gaskets, and is easily removable should it be necessary to 'top up' the oil or replace an H.V. fuse.

**Tank and Cover**

The close fitting steel plate tank and cover are of welded and bolted construction. Gaskets throughout the transformer are of cork-neoprene, a material highly resistant to deterioration.

TABLE I

Weights and oil volumes of new construction as a percentage of old construction

| Type of Voltage Transformer | Oil Volume % | Weight % |
|---|---|---|
| Three-phase .. .. .. | 19·2 | 41·25 |
| Single-phase line-to-line connection .. .. .. .. | 20 | 40 |
| Single-phase line-to-earth connection .. .. .. | 26·2 | 41 |

The whole unit is very compact, requiring only a small amount of oil. Comparative weights and oil volumes for the old and new type of construction are given in Table I.

**Low Voltage Fuses and Terminal Box**

The L.V. fuses and ceramic insulated secondary terminals are housed in a box welded to the end of the tank. The box is fitted with an easily removable slide-on cover.

## FUNDAMENTALS

The compact construction and performance may perhaps be more readily understood if consideration is given to voltage transformer fundamentals.

**Function**

Voltage transformers are employed in conjunction with meters, instruments and relays, and can perform any or all of the following functions:—

(1) Transform the line voltage to a value which is suitable for standard meters, instruments, relays, etc., normally 110 volts or 63·5 volts.
(2) Isolate meters, instruments, relays, etc., from the high voltage side of an installation.
(3) Produce a residual secondary voltage for the operation of relays.

**Determination of Size**

The essential components are the same as for any ordinary power transformer, namely, an iron core, a primary winding, a secondary winding and insulation.

In a power transformer the size of these components, and consequently the size of the complete unit, is largely dependent upon the output, the cooling arrangements and the insulation appropriate to the voltage.

A voltage transformer, however, seldom has an output exceeding a few hundred volt-amperes, and therefore the heat generated is not sufficient to present any serious cooling problem. In many instances ten times normal rated output can be carried and the unit remain within the permissible temperature rise. This is largely due to the size of the primary and secondary conductors being determined by the small values of regulation necessary. It is not uncommon, however, for the size of the wire used in the H.V. coils to be determined by the minimum required to ensure a mechanically sound and robust coil.

The number of turns are arrived at from the primary voltage and a safe value of volts per turn to secure the necessary insulation strength.

The size and number of H.V. coils will depend upon the best arrangement suitable for a satisfactory distribution of both the impulse and induced voltages under the required tests. These tests, together with the applied voltage test, will also determine the size and formation of the major insulation, i.e. between the H.V. coil stack and L.V. coils, core, frame, tank, etc.

The core section will be dependent upon the most economical flux density for the core material selected, and the volts per turn.

It will be seen therefore that the most important factor fixing the dimensions of a voltage transformer is the primary voltage. Consequently it follows that if improved insulation techniques are applied, a corresponding reduction in size will result.

**Operation**

A power transformer is rated in terms of voltage ratio and the maximum secondary output it will deliver without the temperature rise exceeding a specified amount.

A voltage transformer is rated in terms of ratio of primary to secondary voltage, and the maximum burden (VA output) it will deliver without exceeding specified limits of error.

These errors are of two kinds:—

(a) Ratio error.
(b) Phase angle error.

The ratio error is the difference between the actual measured ratio and the nominal ratio, expressed as a percentage of the nominal ratio. It is positive if the secondary voltage exceeds the nominal value and negative if less than nominal.

The percentage ratio error is $\dfrac{K_n V_s - V_p}{V_p} \times 100$

where $K_n$ = the nominal ratio (i.e. rated primary voltage to rated secondary voltage)

$V_s$ = the actual secondary terminal voltage

$V_p$ = the actual primary terminal voltage.

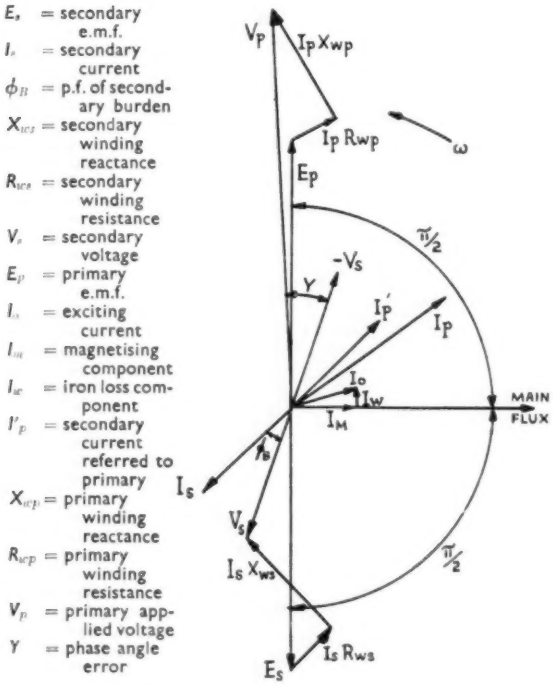



*Fig. 6—Vector diagram of a voltage transformer*

The phase angle error 'Y' in Fig. 6 is the difference of phase between the primary and reversed secondary voltages. It is said to be positive when the reversed secondary voltage vector leads the primary voltage vector, and negative when the reversed secondary voltage vector lags behind the primary voltage vector. It is generally expressed in minutes.

The theory of a voltage transformer is similar to that of a power transformer as will be seen from the vector diagram (Fig. 6). A study of this will show that the errors are largely due to the resistance and reactance of the windings and the VA and power factor of the connected secondary burden.

One factor influencing the reactance is the gap between the H.V. and L.V. coils, which is determined by the method of insulation for a given voltage level. The solid cable paper type of construction employed in these new transformers considerably reduces this gap and thus permits a reduction in errors.

The use of high grade silicon steel for the core allows a higher working flux density and therefore a reduction in core section and/or turns, thereby reducing the winding resistance. The smaller number of turns also assists in further reducing the reactance.

Unlike a power transformer, the exciting current $I_0$ is generally a considerable proportion of the primary current when the secondary burden is connected. With the secondary open-circuited this exciting current acts in a similar manner to the current of a low power-factor burden in the primary windings, and results in an impedance drop. Therefore when on no-load, a voltage transformer has both ratio and phase angle errors. If this exciting current is excessive, then the tendency is to cause a leading or positive phase error, especially when the secondary burden is small. It follows that if the exciting current is reduced by the use of high grade material for the core, a reduction of errors will be achieved.

Summarising therefore, for a given voltage level the most important items determining the errors are the methods and quality of the insulation, and the electromagnetic characteristics of the core material.

**Electromagnetic Requirements**

The electromagnetic requirements for voltage transformers can broadly be divided into two parts; those that are necessary for the operation of instruments and meters, and those necessary for use with protective relays. For British practice the former are laid down in B.S. 81 : 1936 and the latter in B.S. 2046 : 1953.

These new transformers have been built to B.S. 81 and also incorporate the relevant requirements of B.S. 2046, so that the same transformer

TABLE II

Limits of error for measuring-type voltage transformers

| Class of Accuracy | Use | Limit of Error | | | |
|---|---|---|---|---|---|
| | | At 90 to 100% of rated voltage and 25 to 100% of rated secondary burden at unity p.f. | | At 90 to 106% of rated voltage and 10 to 50% of rated secondary burden at 0·2 p.f. | |
| | | Ratio error + or − | Phase difference + or − | Ratio error + or − | Phase difference + or − |
| A | With sub-standard indicating wattmeters .. | 0·5% | 20 min | 0·5% | 40 min |
| B | With industrial metering, first-grade indicating instruments and wattmeters or for synchronising .. .. .. .. | 1·0% | 30 min | 1·0% | 70 min |
| C | With first-grade voltmeters .. .. .. | 2·0% | 60 min | — | — |
| D | For purposes where ratio is of less importance than for A, B or C .. .. .. .. | 5·0% | — | — | — |

TABLE III

Limits of error for protective-type voltage transformers

| Applied primary voltage | Burden at unity power factor | Ratio error | Phase difference |
|---|---|---|---|
| % rated voltage | % rated burden | % | Degrees |
| 50 and 110 | 100 to 25 | ± 2·5 | ± 2·5 |
| 5 and 10 | 100 to 25 | ± 5 | ± 5 |

can be used for both metering and protection. Whilst it is not the author's intention to reiterate all the requirements of these British Standards, it is felt that the following points are of interest.

*Metering Requirements to B.S.* 81 : 1936

The ideal transformer would of course produce a secondary voltage which is an exact replica of the primary voltage. Study of the vector diagram has shown, however, that this is not possible. B.S. 81 therefore lays down limits of both ratio and phase angle error for certain conditions of rated voltage and rated secondary burden. These limits are given in Table II. The limits of error refer to the errors as determined at the terminals of the primary and secondary windings, and exclude any protective resistors or fuses.

Class B accuracy is used extensively, the other classes having fallen more or less into disuse. There are also two further accuracy classes, namely AL and BL, which are for laboratory use only and are not considered in this article.

*Protective Requirements to B.S.* 2046 : 1953

The ratio and phase angle error for voltage transformers used solely for the operation of relays can be much larger than those required for metering ; the limits are given in Table III and apply :—

(1) in a single-phase transformer, to the voltages at the terminals,

(2) in a three-phase transformer with the primary star point insulated, to the line-to-line voltage,

TABLE IV

Characteristics and application of Categories X, Y and Z voltage transformers

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| | Characteristics | | | Application |
| Category of transformer | Voltage applied to transformer with:<br>*a.* Any one primary phase short-circuited between line terminal and earth terminal; and<br>*b.* Secondary measuring winding, if any, open-circuited; and<br>*c.* Residual voltage winding, if any, in broken delta. | Duration of conditions in Column 2. | Secondary residual voltage for conditions in Column 2 if transformer has a residual voltage winding. | Earthing condition of star-point or points of power system. |
| X | Rated line-to-earth voltage between line terminal and earth terminal of each non-short-circuited phase; voltage on one such phase being 120° from voltage on other phase. | Not exceeding 30 seconds | 63·5 volts | Star-point or points earthed solidly, and voltage of sound phases to earth not exceeding 20 per cent above normal. |
| Y | Rated three-phase line-to-line-balanced voltage between all three line terminals so applied that rated line-to-line voltage also occurs between line terminal and earth terminal of each non-short-circuited phase. | Not exceeding 30 seconds | 190 volts | Star-point or points earthed through short-time rated resistor, impedance, or arc-suppression coil. |
| Z | | Not exceeding 125 hr per annum, with a max. of 8 hr in any 24 hr. | 190 volts | Star-point or points earthed through arc-suppression coil, or insulated from earth. |

(3) in a three-phase transformer for use with the primary star point earthed, to the line-to-line voltage, or alternatively, if the secondary star point is accessible, to the voltage between line and star point.

In addition, B.S. 2046 divides voltage transformers into categories (see Table IV) according to whether or not they are suitable for certain conditions of system earthing, and also standardises transformers that are capable of producing a residual voltage.

It would perhaps be appropriate to include here a brief description of the principles of a residual voltage transformer.

**Residual Voltage Transformers**

Fig. 7 shows the connection for obtaining a residual or zero-sequence voltage which can be used to operate the voltage coil of a directional earth fault relay.

The star-connected primary windings of a three-phase voltage transformer are connected to the circuit being protected, the neutral point being solidly earthed. The secondary windings are connected in delta, the circuit being completed by the relay voltage coil. This arrangement is known as a broken delta connection.

*Category X Conditions, B.S.* 2046

Consider the case where the system is solidly earthed. When the system is healthy the pressures on the primary windings will have an instantaneous sum of zero, and consequently there will be no voltage across the relay coil connected in the secondary winding. If an earth fault occurs from one line, then the main line-to-earth voltages will have a resultant, which will appear across the relay coil. The closer the fault is to the transformer the greater will be the secondary residual voltage. Thus in the extreme case it can be considered that one phase of the voltage transformer primary winding is short-circuited, so that the value of the voltage appearing across the relay coil will be the same as that of the secondary winding phase voltage, which for a standard transformer would be 63·5 volts.

*Categories Y and Z Conditions, B.S.*2046

Now consider the case where the system is earthed through a high resistance, impedance or arc-suppression coil, again taking the extreme condition where one phase of the voltage transformer primary winding is short-circuited. Under earth fault conditions the maximum voltage that will appear across the earthing resistance or impedance is equivalent to the system phase voltage, and therefore across both the transformer primary phases 'a' and 'b' there will be a pressure equal to $\sqrt{3}$ times the normal line-to-neutral voltage. A corresponding increase in pressure will occur in the transformer secondary phases 'a' and 'b', the vector sum of which will appear at the relay coil terminals. This will have a value equal to the transformer secondary phase voltage times $(\sqrt{3})^2$. For a standard transformer this voltage will be the product of 3 times 63·5 volts, i.e., 190 volts approximately.

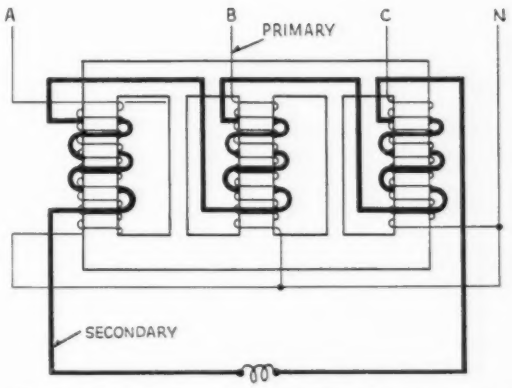



*Fig. 8—5-limb core and windings for a residual voltage transformer*

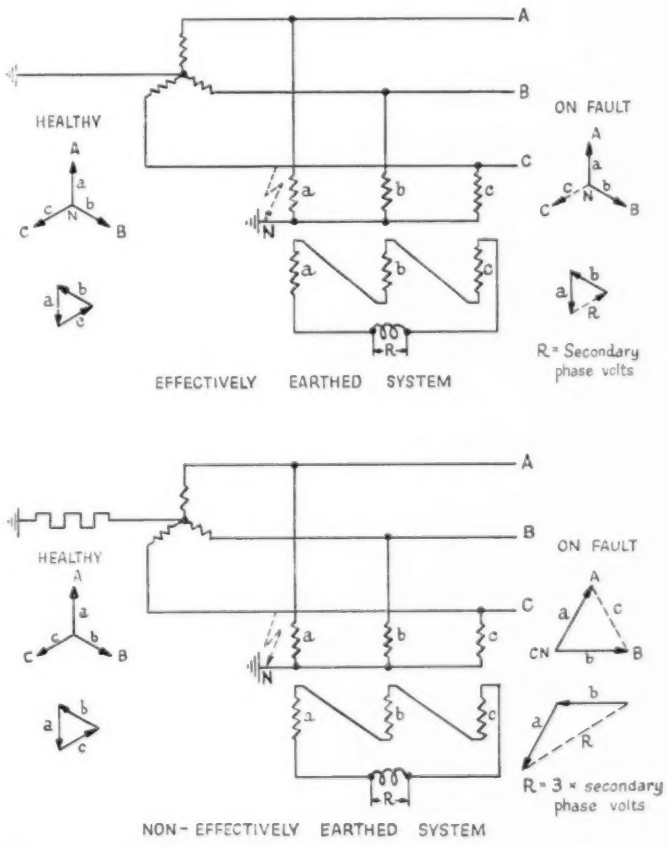



*Fig. 7—Connections for residual voltage transformers*

*Requirements of B.S.*2046 : 1953

B.S. 2046 requires that when these maximum system fault conditions are simulated on test, the ratio error and phase difference between the primary and secondary residual voltages of a three phase residual voltage transformer shall not exceed $\pm 10\%$ and $\pm 10$ degrees respectively. This is with from 25 to 100% of the rated residual burden connected across the broken delta of the secondary winding.

To safeguard against inadvertent relay tripping a further requirement is that with rated balanced three-phase voltage applied to the primary windings of the transformer, and with rated burden connected to the residual voltage terminals, the voltage at these terminals shall not exceed 5 volts.

*Selection of Category Y or Z*

Since the voltage applied to the transformer primary windings under

system fault conditions may be $\sqrt{3}$ times the normal value, the flux density in the core will rise by an equivalent amount. If a standard transformer is used, designed with an economical flux density of say 13,000 gauss, then with an increase of $\sqrt{3}$ times this value, the exciting current will increase many times its normal value due to saturation of the core material. This, in time, would result in the transformer winding burning out.

The obvious way to counteract this is to design the transformer so that under system fault conditions the exciting current is restricted to some safe value. Mainly, this means that for normal conditions the flux density will require to be in the order of say 7,500 gauss, i.e. $13{,}000 \div \sqrt{3}$. This will require a correspondingly larger core section, and so a larger and more expensive transformer.

Due to space restrictions, particularly for voltage transformers associated with indoor type switchgear, it has been found necessary to have two categories of transformers. Firstly where the duration of the fault will not exceed 30 seconds (Category Y) and secondly where the fault may remain for several hours (Category Z).

The transformer exciting current can rise to a fairly high value for 30 seconds without causing any damage; consequently a smaller and more economical unit can be constructed for Category Y than for Category Z.

A further consideration is the additional stress on the insulation due to the increase in pressure. To withstand this condition continuously would demand a higher insulation level. Thus, again on the grounds of size and economics, the requirement for a Category Z transformer is that it will satisfactorily withstand the fault voltage for a period not exceeding 125 hours per annum, with a maximum of 8 hours in any 24 hours.

*Construction Peculiarities*

A residual voltage cannot be obtained by using the windings of a normal three-phase three-limb type of transformer, since the only path for the magnetic flux with one primary phase short-circuited will be through air. The reluctance of the air path will be so high that the residual voltage will almost be non-existent on the secondary side. It is therefore necessary to provide a low reluctance return path for the fluxes generated in the two fully excited limbs; hence two further limbs are added, making a five-limb core as shown in Fig. 8.

An alternative method is to have three separate single-phase transformers suitable for connection between line and earth. The primary windings are connected in star, the neutral point solidly earthed, and the secondary windings connected in broken delta. Each transformer provides its own magnetic flux return path.

Some supply authorities prefer the five-limb construction whilst others prefer the bank of three single-phase units. In this new range of 33 kV voltage transformers both requirements have been provided for.

It is usual to combine the characteristics for protective and metering transformers in one unit, and so it is common to have a three-phase transformer with a star-connected primary winding, a star-connected secondary winding for metering, and a delta-connected tertiary winding to give a residual voltage. This would possibly be rated at say 200 VA, Class B to B.S. 81 and Category Z to B.S. 2046.

**Protective Transformers Category W, B.S. 2046 : 1953**

A Category W transformer is a single or three-phase unit, the primary winding or windings of which is or are not connected to earth. Provided that the insulation is appropriate, a Category W transformer is suitable for use under any conditions of system earthing, but it cannot produce a residual voltage.

## TESTS AND PERFORMANCE

These new transformers have been satisfactorily subjected to both routine and type tests, in accordance with the relevant requirements of B.S. 81 and B.S. 2046, and from the bushing arrangement aspect with B.S. 223, rating 106.

At present none of these specifications make provision for impulse voltage tests. However, a set of tests have been carried out, and satisfactorily withstood, on a complete unit at an impulse voltage level of 250 kV, this being considerably in excess of the established figure of 200 kV for a 33 kV system.

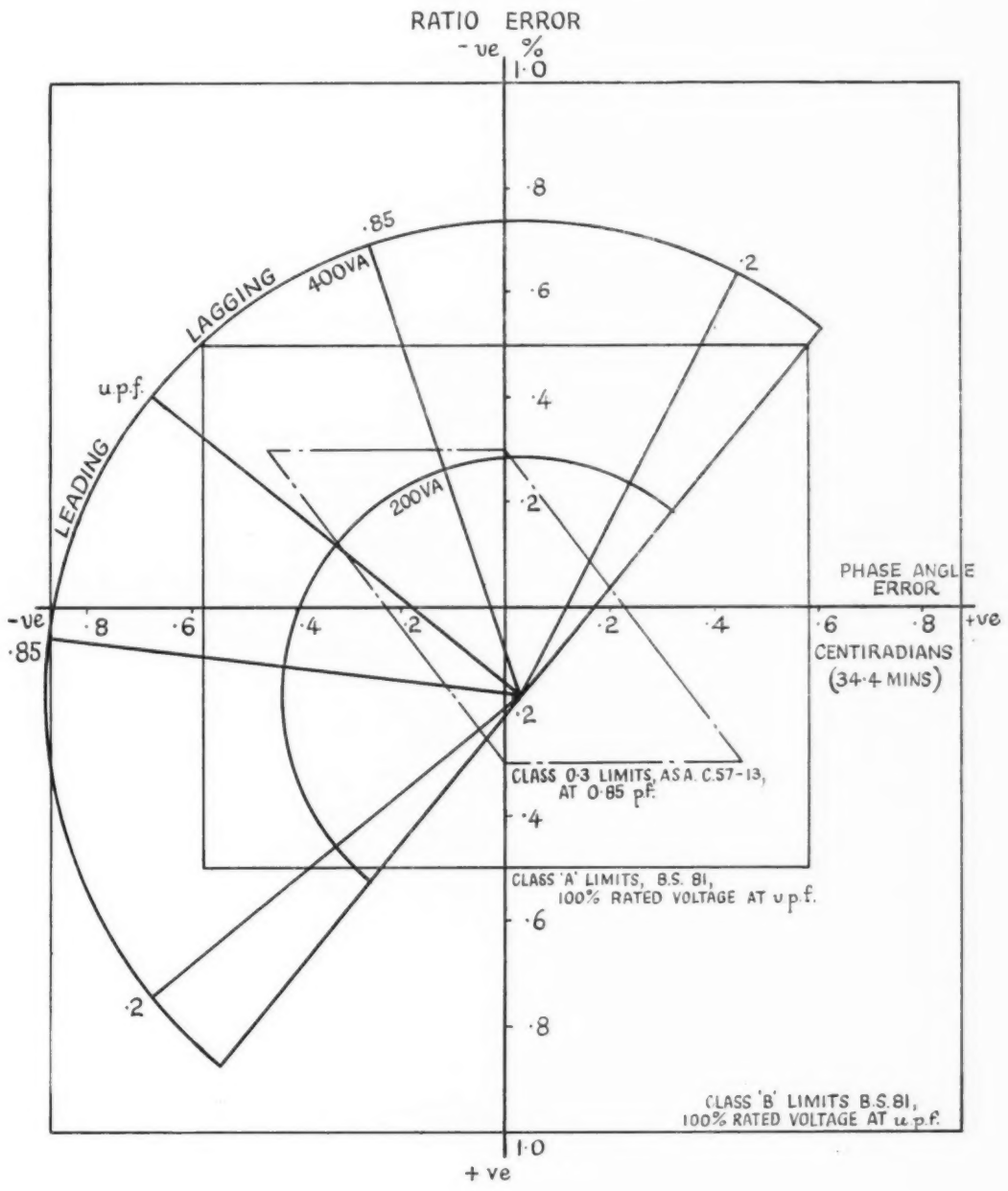



*Fig. 9—Ratio and phase angle errors at 100% rated voltage*

The standard series of transformers have a rated burden of 200 VA, accuracy Class B to B.S. 81. Although the British Standards only require tests for temperature rise to be carried out at the rated burden, one unit was tested with a burden of 2 kVA, i.e. ten times the normal burden. The temperature rises were within the limits of B.S. 81.

The single-phase unit for line-to-line connection, and the three-phase three-limb star/star-connected transformer are in Category W. The single-phase unit for line-to-earth connection and the three-phase five-limb transformer connected star/star/delta are in Category Z and are also suitable for Categories X and Y.

On a recently completed contract of sixty single-phase units for a supply authority in the U.S.A. an accuracy classification of 0·3 to ASA. C57. 13-1953 was required at a rated burden of 200 VA. The limits of error in this classification are even smaller than in Class A B.S. 81 and were obtained without any increase in size by using a high permeability anisotropic silicon steel core material, and by minor modifications to the coils. A typical set of ratio error and phase angle error values for these units are shown in Fig. 9. These errors fall well within the limits of Class A for a rated burden of 200 VA, and Class B for a rated burden of 400 VA.

## PROCESSING

To take full advantage of oil impregnated cable paper as an insulating medium, and to ensure satisfaction in service, the transformer assemblies undergo a very exacting method of processing. Briefly, this consists of oven drying under a high degree of vacuum for several days, to remove moisture and air, followed by a further period of vacuum which is terminated by filling the transformer with filtered and degassified oil to B.S. 148. During the filling and for a short period afterwards the vacuum is maintained, ensuring the exclusion of air from the windings and insulation.

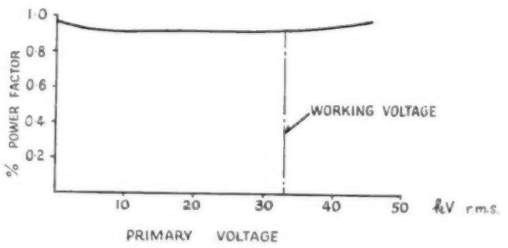



*Fig. 10—Typical power-factor/voltage curve obtained during dielectric loss angle test*

Dielectric loss angle tests are carried out on these transformers, using a Schering bridge and high voltage gas-filled loss-free standard condenser equipment. A typical power-factor/voltage curve is shown in Fig. 10 from which it will be observed that a low power factor is obtained and that the curve is substantially flat up to a point well beyond the working voltage. This important feature ensures that no deterioration of the insulation occurs due to internal ionisation at the normal working voltage, and hence a prolonged service life is an inherent characteristic of this type of transformer.

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